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FILED
JUN 1 3 2008
RICHARD W. WIEKING
CLERK, U.S. DISTRICT COURT
NORTHERN DISTRICT OF CALIFORNIA

UNITED STATES DISTRICT COURT

NORTHERN DISTRICT OF CALIFORNIA

UNIVERSITY OF PITTSBURGH OF THE COMMONWEALTH SYSTEM OF HIGHER EDUCATION d/b/a UNIVERSITY OF PITTSBURGH, a Pennsylvania non-profit corporation (educational), Plaintiff, v. VARIAN MEDICAL SYSTEMS, INC., a Delaware corporation, Defendant.	CV Case No. 08 2973 BZ **COMPLAINT FOR PATENT INFRINGEMENT** **DEMAND FOR JURY TRIAL**

Plaintiff UNIVERSITY OF PITTSBURGH OF THE COMMONWEALTH SYSTEM OF HIGHER EDUCATION d/b/a UNIVERSITY OF PITTSBURGH ("UPitt" or "University of Pittsburgh") for its complaint against defendant VARIAN MEDICAL SYSTEMS, INC. ("Varian" or "Defendant") alleges as follows:

PARTIES

1. Plaintiff UPitt is a non-profit corporation with its principal place of business at 4200 Fifth Ave, Pittsburgh, Pennsylvania 15260.

2. UPitt was founded in 1787 as a small, private school, known as the Pittsburgh Academy, which was located in a log cabin near Pittsburgh's three rivers. In the 220 years since, the University of Pittsburgh has evolved into an internationally recognized center of learning and research. One such area of recognized research relates to medical use of radiation for treatment and diagnosis. The University of Pittsburgh owns valuable intellectual property rights in this and other technology areas.

3. On information and belief, defendant Varian is a Delaware corporation with its principal place of business at 3100 Hansen Way, Palo Alto, California 94304-1030.

4. On information and belief, Varian manufactures, sells and services equipment and software for the medical use of radiation for treatment and diagnosis.

JURISDICTION AND VENUE

5. This action arises under the patent laws of the United States, 35 U.S.C. §§ 1 *et seq.*, for infringement by Varian of patents owned by UPitt. This Court has jurisdiction over the subject matter of this action pursuant to 28 U.S.C. §§ 1331 and 1338.

6. This Court has personal jurisdiction over Varian because Varian does business in California and has sufficient contacts with the State of California to satisfy both the requirements of due process and Rule 4(k)(2) of the Federal Rules of Civil Procedure.

7. Venue is proper in this judicial district pursuant to 28 U.S.C. §§ 1391(b) & (c) and 1400(b).

INTRADISTRICT ASSIGNMENT

8. Pursuant to Civil L.R. 3-2(c), this action for patent infringement is subject to assignment on a district-wide basis.

COUNT ONE

(Infringement of U.S. Patent No. 5,727,554 by Varian)

9. UPitt re-alleges and incorporates by reference the allegations stated in paragraphs 1 through 8.

10. Pursuant to the assignments attached as Exhibits 1 and 2, UPitt is the owner of United States Patent No. 5,727,554 (the 554 Patent), entitled "Apparatus Responsive to Movement of a Patient During Treatment/Diagnosis." The 554 Patent was duly and legally issued by the Patent and Trademark Office on March 17, 1998. A true and correct copy of the 554 Patent is attached as Exhibit 3.

11. Varian has infringed and continues to infringe the 554 Patent by importing, making, using, offering for sale and/or selling products, in the United States that embody or otherwise practice one or more of the claims of the 554 Patent, or by otherwise contributing to infringement or inducing others to infringe the 554 Patent.

12. On information and belief, Varian's infringement has been with full knowledge of the 554 Patent and willful; thus, this is an exceptional case under 35 U.S.C. § 285, and UPitt is accordingly entitled to an award of its attorneys' fees.

13. Varian's infringement has injured and damaged UPitt. The University of Pittsburgh is entitled to recover damages adequate to compensate UPitt for Varian's infringing activities in an amount to be determined at trial, but in no event less than a reasonable royalty, together with interest and costs.

COUNT TWO

(Infringement of U.S. Patent No. 5,784,431 by Varian)

14. UPitt re-alleges and incorporates by reference the allegations stated in paragraphs 1 through 13.

15. Pursuant to the assignments attached as Exhibits 1 and 4, UPitt is the owner of United States Patent No. 5,784,431 (the 431 Patent), entitled "Apparatus for Matching X-Ray Images with Reference Images." The 431 Patent was duly and legally issued by the Patent and Trademark Office on July 21, 1998. A true and correct copy of the 431 Patent is attached as Exhibit 5.

16. Varian has infringed and continues to infringe the 431 Patent by importing, making, using, offering for sale and/or selling products, in the United States that embody or otherwise practice one or more of the claims of the 431 Patent, or by otherwise contributing to infringement or inducing others to infringe the 431 Patent.

17. On information and belief, Varian's infringement has been with full knowledge of the 431 Patent and willful; thus, this is an exceptional case under 35 U.S.C. § 285, and UPitt is accordingly entitled to an award of its attorneys' fees.

18. Varian's infringement has injured and damaged UPitt. The University of Pittsburgh is entitled to recover damages adequate to compensate UPitt for Varian's infringing activities in an amount to be determined at trial, but in no event less than a reasonable royalty, together with interest and costs.

PRAYER FOR RELIEF

WHEREFORE, UPitt requests that the Court enter judgment in favor of UPitt and against Varian as follows:

(a) adjudicating and declaring that Varian has infringed, contributorily infringed, and actively induced others to infringe the 554 and 431 Patents;

(b) awarding UPitt damages in an amount sufficient to compensate UPitt for Varian's infringement, contributory infringement, and active inducement of others' infringement of the 554 and 431 Patents, but not less than a reasonable royalty;

(c) awarding pre-judgment interest, costs, and expenses to UPitt pursuant to 35 U.S.C. § 284;

(d) awarding increased damages, pursuant to 35 U.S.C. § 284, by reason of Varian's willful infringement of the 554 and 431 Patents;

(e) declaring this case exceptional under 35 U.S.C. § 285 and awarding UPitt its reasonable attorney fees, expenses, and costs incurred; and

(f) granting UPitt such other and further relief as this Court may deem just and proper, or that UPitt may be entitled to as a matter of law or equity.

Dated: June 16, 2008

Respectfully submitted,

MORGAN, LEWIS & BOCKIUS LLP

By Daniel Johnson Jr
Daniel Johnson, Jr.
(State Bar No. 57409)

Attorneys for Plaintiff
UNIVERSITY OF PITTSBURGH

DEMAND FOR JURY TRIAL

UPitt hereby requests a trial by jury.

Dated: June 16, 2008

Respectfully submitted,

MORGAN, LEWIS & BOCKIUS LLP

By Daniel Johnson Jr.

Daniel Johnson, Jr.
(State Bar No. 57409)

Attorneys for Plaintiff
UNIVERSITY OF PITTSBURGH

EXHIBIT A

Intellectual Property Assignment

THIS ASSIGNMENT is made as of June 16, 2008, by Carnegie Mellon University, a Pennsylvania non-profit corporation (the "**Assignor**"), and University of Pittsburgh – Of the Commonwealth System of Education, a Pennsylvania non-profit corporation (the "**Assignee**").

WHEREAS, Assignor and Assignee have entered into that certain Patent Purchase Agreement dated June 16, 2008 (the "**Patent Assignment Agreement**"), which, along with the promises contained therein, constitute mutual consideration for the promises herein;

NOW, THEREFORE, for consideration the adequacy and receipt of which is hereby acknowledged, the Assignor hereby:

1. ASSIGNS to Assignee all of its right, title and interest in and to United States Patents No. 5,727,554 and 5,784,431 (the "**Patents**").

2. AGREES to execute, verify and deliver such documents and perform such other acts, at Assignee's cost and expense, as Assignee may reasonably request for use in applying for, obtaining, perfecting, evidencing, sustaining and enforcing the Patents and the assignment thereof.

IN WITNESS WHEREOF, Assignor and Assignee have executed this Assignment as of the day and year first above written.

ASSIGNOR:

CARNEGIE MELLON UNIVERSITY
a Pennsylvania non-profit corporation

By: Susan Burkett

Name: Susan Burkett

Title: Associate Vice President

ASSIGNEE:

UNIVERSITY OF PITTSBURGH – OF THE COMMONWEALTH SYSTEM OF EDUCATION,
a Pennsylvania non-profit corporation

By: Jerome Cochran

Name: Jerome Cochran

Title: Executive Vice Chancellor

08/715839

ASSIGNMENT

In consideration of One Dollar ($1.00) and other good and valuable consideration, the receipt of which is hereby acknolwedged, we **Andre M. Kalend, Joel Greenberger, Karun B. Shimoga, Charalambos N. Athanassiou, and Takeo Kanade** citizens, respectively, of Zaire, the United States of America, India, Greece, and Japan residing, respectively, at 103 Trotwood Drive, Monroeville, PA 15146; 749 Chestnut Street, Sewickley, PA 15143; 5030 Centre Avenue, Apt. #560, Pittsburgh, PA 15213; 515 S. Aiken Ave., Apt. #711, Pittsburgh, PA 15232; 130 Penrose Drive., Pittsburgh, PA 15208;

Hereby sell, assign and transfer to the **University of Pittsburgh of the Commonwealth System of Higher Education,** a non-profit Pennsylvania corporation, having a place of business at 911 William Pitt Union, Pittsburgh, Pennsylvania 15260, in the County of Allegheny and Commonwealth of Pennsylvania, its successors, assigns and legal representatives, my/our entire right, title and interest, forall countries, in and to any and all inventions and improvements which are disclosed and claimed, andany and all improvements which are disclosed but not claimed, in United States Patent Application **APPARATUS RESPONSIVE TO MOVEMENT OF A PATIENT DURING TREATMENT/DIAGNOSIS** executed respectively by us on even date herewith and in and to said application and all divisional, continuing, substitute, renewal, reissue and all other applications for Letters Patent which have been or shall be filed on any of said improvements disclosed in said application; and in and to all original and reissued patents which have been or shall be issued on said improvements;

Authorized and request the Commissiioner of Patents and Trademarks to issue to said Assignee, the Uniserity of Pittsburgh of the Commonwealth System of Higher Education, its successors, assigns and legal representatives, in accordance with this assignment, any and all United States Letters Patent on said improvements, or any of them, disclosed in said application;

Agree that, when requested, without charge to but at the expense of said Assignee, its successors, assigns and legal representatives, to carry out in good faith the intent and purpose of this assignment I/we will, for all countries, execute all divisional, continuing, substitute, renewal, reissue, and all other patent applications on ay and all said improvements; execute all rightful oaths and other papers; communicate to said Assignee, its successors, assigns, and representatives, all facts known to me/us relating tos aid improvements and the history thereof; testify in all legal proceedings; and generally do everything possible which said Assignee, its successors, assigns or representatives shall consider desirable for aiding in securing, maintaining and enforcing proper patent protection for said improvemnts, and for vesting title to said improvements and all applications for patents and all patents on said improvements, in said Assignee, its successors, assigns and legal representatives;

Covenant with said Assignee, its successors, assigns and legal representatives that I/we have made to others no assignment, grant, mortgage, license or other agreement affecting the rights and property herein conveyed, and that I/we have full right to convey the same as herein expressed.

DATE 8 22 96 ______________________ (SEAL)
ANDRE M. KALEND

Commonwealth of Pennsylvania)
):
County of Allegheny)

Before me this 27th day of August, 1996, personally appeared Andre Kalend, to me personally known to be the person who is described herein and who executed the above instrument, and he acknowledged to me that he executed the same of his own free will for the purposes herein set forth.

Patricia A Lang
Notary Public

(Affix Seal Here)

Notarial Seal
Patricia A. Lang, Notary Public
Pittsburgh, Allegheny County
My Commission Expires Nov. 22, 1997
Member, Pennsylvania Association of Notaries

DATE 8-28-96 ____________________ (SEAL)
JOEL GREENBERGER

State of Pennsylvania)
):
County of Allegheny)

Before me this 28th day of August, 1996, personally appeared Joel Greenberger, MD, to me personally known to be the person who is described herein and who executed the above instrument, and he acknowledged to me that he executed the same of his own free will for the purposes herein set forth.

Patricia A Lang
Notary Public

(Affix Seal Here)

Notarial Seal
Patricia A. Lang, Notary Public
Pittsburgh, Allegheny County
My Commission Expires Nov. 22, 1997
Member, Pennsylvania Association of Notaries

DATE Aug 13, '96 ____________________ (SEAL)
KARUN B. SHIMOGA

Commonwealth of Pennsylvania)
):
County of Allegheny)

Before me this 13th day of Aug., 1996, personally appeared KARUN SHIMOGA, to me personally known to be the person who is described herein and who executed the above instrument, and he acknowledged to me that he executed the same of his own free will for the purposes herein set forth.

Emma Jean Scavincky
Notary Public

Notarial Seal
Emma Jean Scavincky, Notary Public
Pittsburgh, Allegheny County
My Commission Expires Dec. 14, 1996
Member, Pennsylvania Association of Notaries

(Affix Seal Here)

DATE Aug 13, 1996 ____________________ (SEAL)
CHARALAMBOS N. ATHANASSIOU

Commonwealth of Pennsylvania)
):
County of Allegheny)

Before me this 13th day of Aug., 1996, personally appeared Charalambos N. Athanassiou, to me personally known to be the person who is described herein and who executed the above instrument, and he acknowledged to me that he executed the same of his own free will for the purposes herein set forth.

Emma Jean Scavincky
Notary Public

Notarial Seal
Emma Jean Scavincky, Notary Public
Pittsburgh, Allegheny County
My Commission Expires Dec. 14, 1996
Member, Pennsylvania Association of Notaries

(Affix Seal Here)

DATE Aug 26, 1996 ____________________ (SEAL)
TAKEO KANADE

Commonwealth of Pennsylvania)
):
County of Allegheny)

Before me this 26 day of August, 1996, personally appeared ____________________, to me personally known to be the person who is described herein and who executed the above instrument, and he acknowledged to me that he executed the same of his own free will for the purposes herein set forth.

Carolyn S. Krawczykiewicz
Notary Public

Notarial Seal
Carolyn S. Krawczykiewicz, Notary Public
Pittsburgh, Allegheny County
My Commission Expires May 29, 2000
Member, Pennsylvania Association of Notaries

(Affix Seal Here)

US005727554A

United States Patent [19]

Kalend et al.

[11] **Patent Number: 5,727,554**

[45] **Date of Patent: Mar. 17, 1998**

[54] **APPARATUS RESPONSIVE TO MOVEMENT OF A PATIENT DURING TREATMENT/DIAGNOSIS**

[75] Inventors: **Andre M. Kalend**, Monroeville; **Joel Greenberger**, Sewickley; **Karun B. Shimoga**, Pittsburgh; **Charalambos N. Athanassiou**, Pittsburgh; **Takeo Kanade**, Pittsburgh, all of Pa.

[73] Assignee: **University of Pittsburgh of the Commonwealth System of Higher Education**, Pittsburgh, Pa.

[21] Appl. No.: **715,834**

[22] Filed: **Sep. 19, 1996**

[51] **Int. Cl.**^{6} **A61B 6/00**

[52] **U.S. Cl.** **128/653.1**

[58] **Field of Search** 128/630, 653.1, 128/660.03; 364/413.02, 413.13, 413.25, 413.26; 356/375; 378/69, 205

[56] **References Cited**

U.S. PATENT DOCUMENTS

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5,080,100	1/1992	Trotel	128/653.1
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5,214,711	5/1993	Neely et al.	364/413.27 X
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5,446,548	8/1995	Gerig et al.	128/653.1 X
5,482,042	1/1996	Fujita	128/653.1
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Training Models of Shape from Sets of Examples, T.F. Cootes, C.J. Taylor, D.H. Cooper, and J. Graham, pp. 8–18, Proceedings of European Conference on Computer Vision, Genoa, Italy, 1992.

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Feature Extraction from Faces Using Deformable Templates, A.L. Yuille, P.W. Hallinan, and D.S. Cohen, pp. 99–111, International Journal of Computer Vision, 8:2, 1992.

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Motion Tracking with an Active Camera, D. Murray and A. Basu, pp. 449–459, IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 16, No. 5, May 1994.

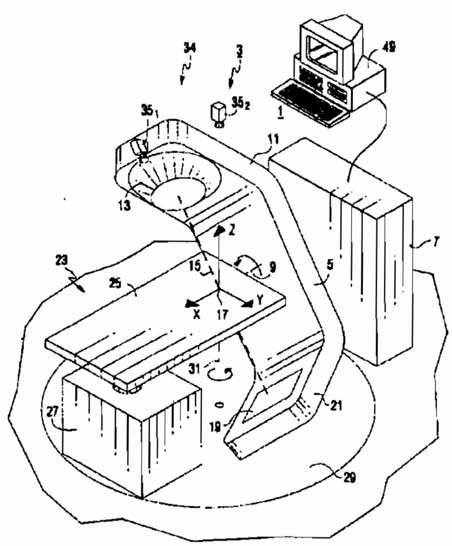
Primary Examiner—Francis Jaworski

Attorney, Agent, or Firm—Richard V. Westerhoff; Eckert Seamans Cherin & Mellott, LLC

[57] **ABSTRACT**

A camera generates digital image signals representing an image of one or more natural or artificial fiducials on a patient positioned on treatment or diagnosis equipment. A processor applies multiple levels of filtering at multiple levels of resolution to repetitively determine successive fiducial positions. A warning signal is generated if movement exceeds certain limits but is still acceptable for treatment. Unacceptable displacement results in termination of the treatment beam. Tracking templates can be generated interactively from a display of the digital image signals or through automatic selection of an image having the median correlation to an initial template. A gating signal synchronized to patient breathing can be extracted from the digital image signals for controlling the radiation beam generator.

22 Claims, 12 Drawing Sheets



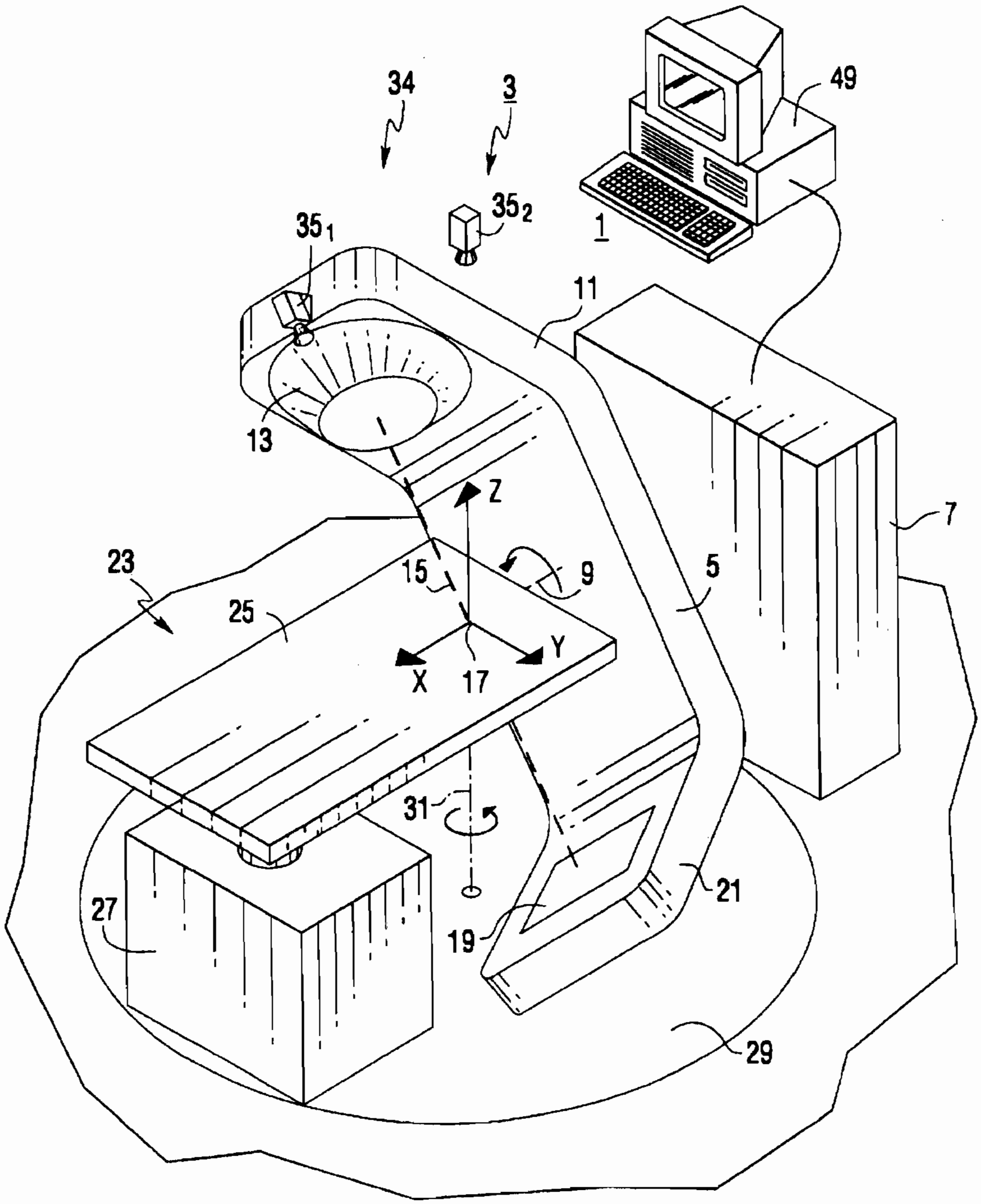


FIG. 1

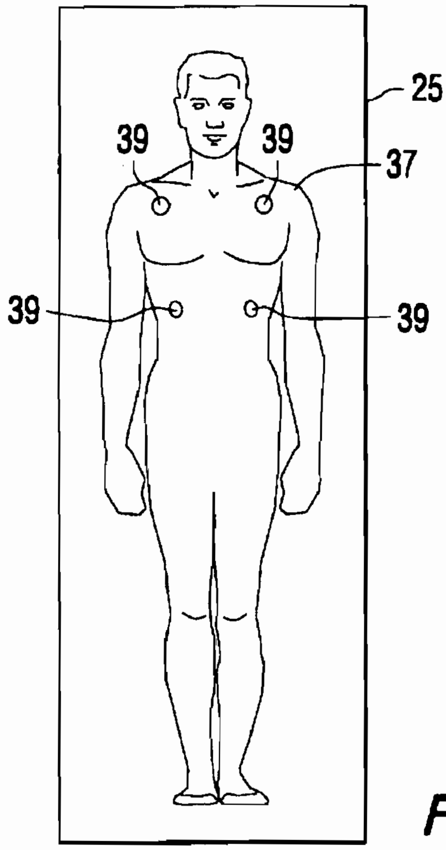

25
39
39
37
39
39

FIG. 2

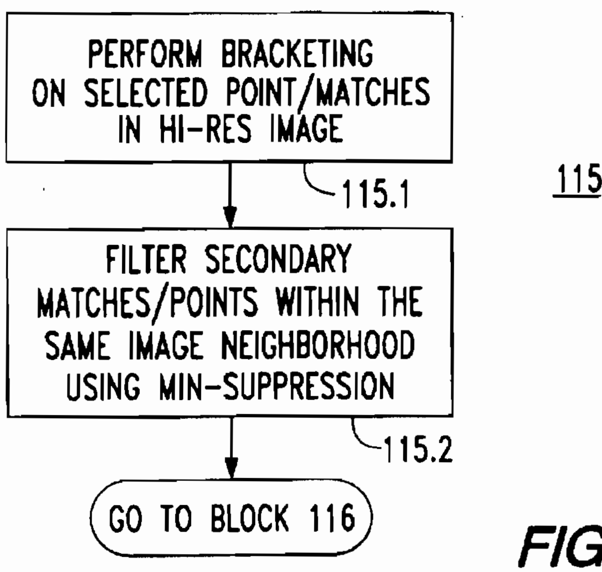
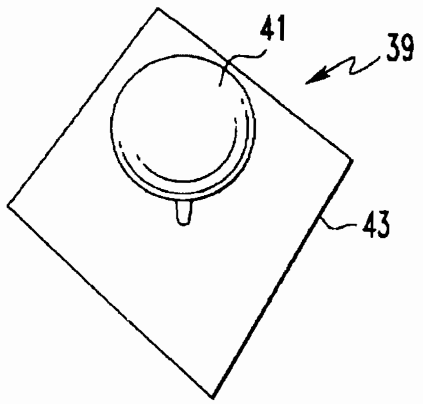
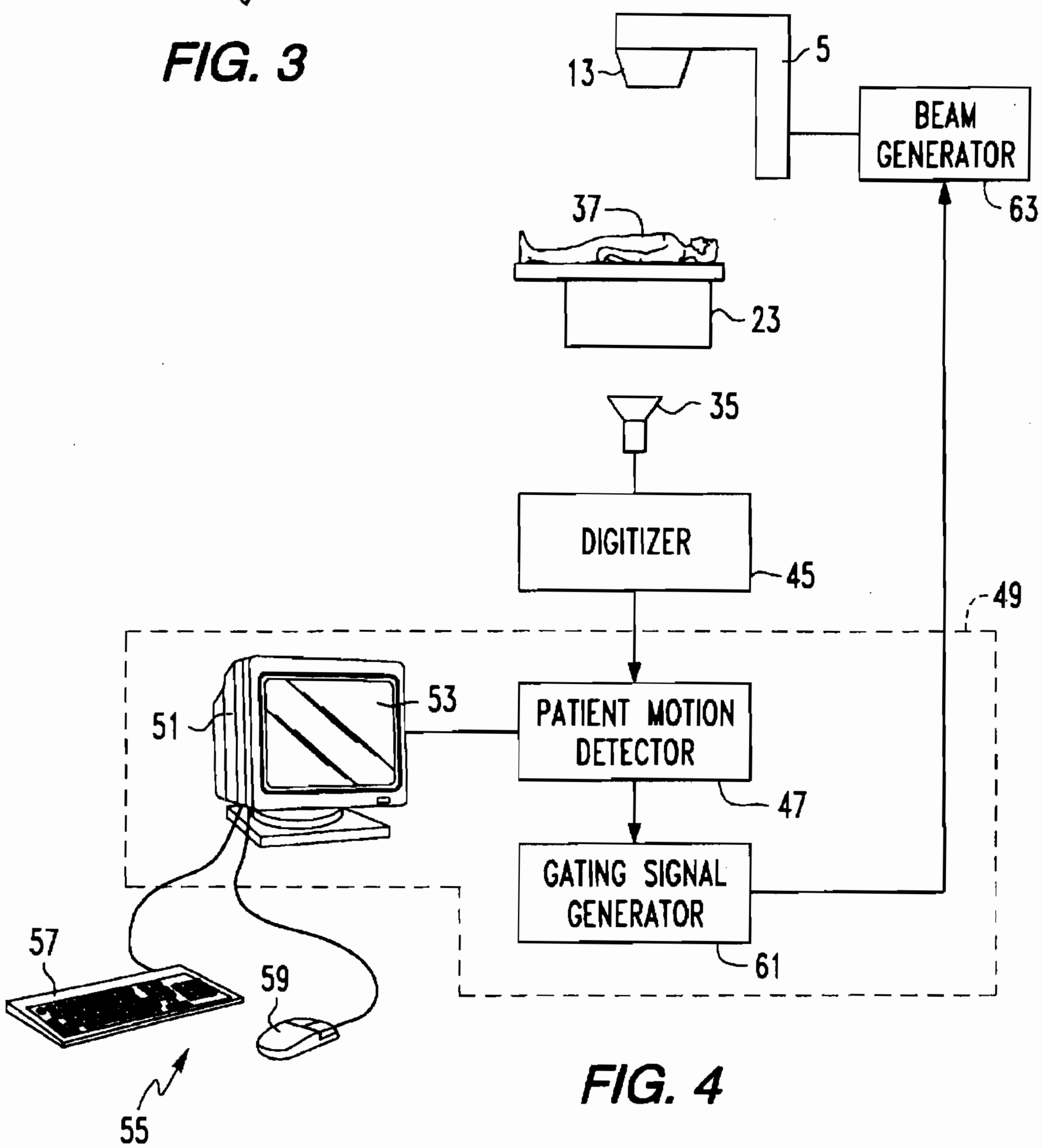

PERFORM BRACKETING ON SELECTED POINT/MATCHES IN HI-RES IMAGE
115.1
115
FILTER SECONDARY MATCHES/POINTS WITHIN THE SAME IMAGE NEIGHBORHOOD USING MIN-SUPPRESSION
115.2
GO TO BLOCK 116

FIG. 9



41
39
43

FIG. 3



13
5
BEAM GENERATOR
63
37
23
35
DIGITIZER
45
49
51
53
PATIENT MOTION DETECTOR
47
GATING SIGNAL GENERATOR
61
57
59
55

FIG. 4

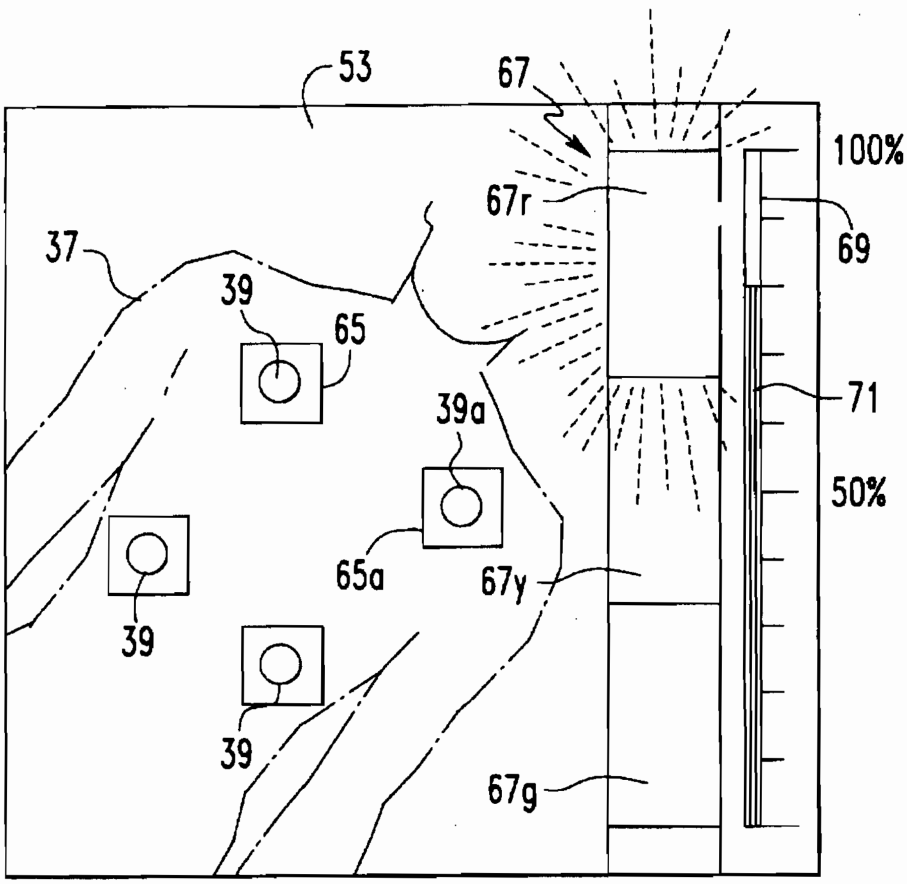

53
67
67r
100%
69
37
39
65
39a
71
50%
39
65a
67y
39
39
67g

FIG. 5

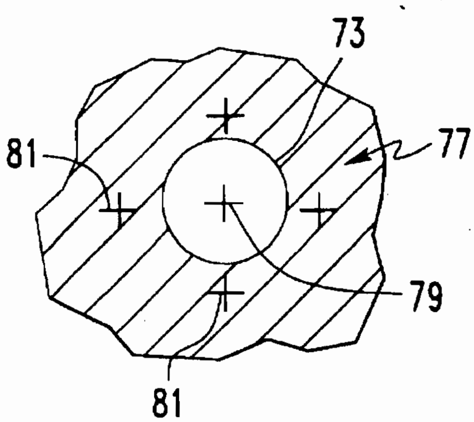
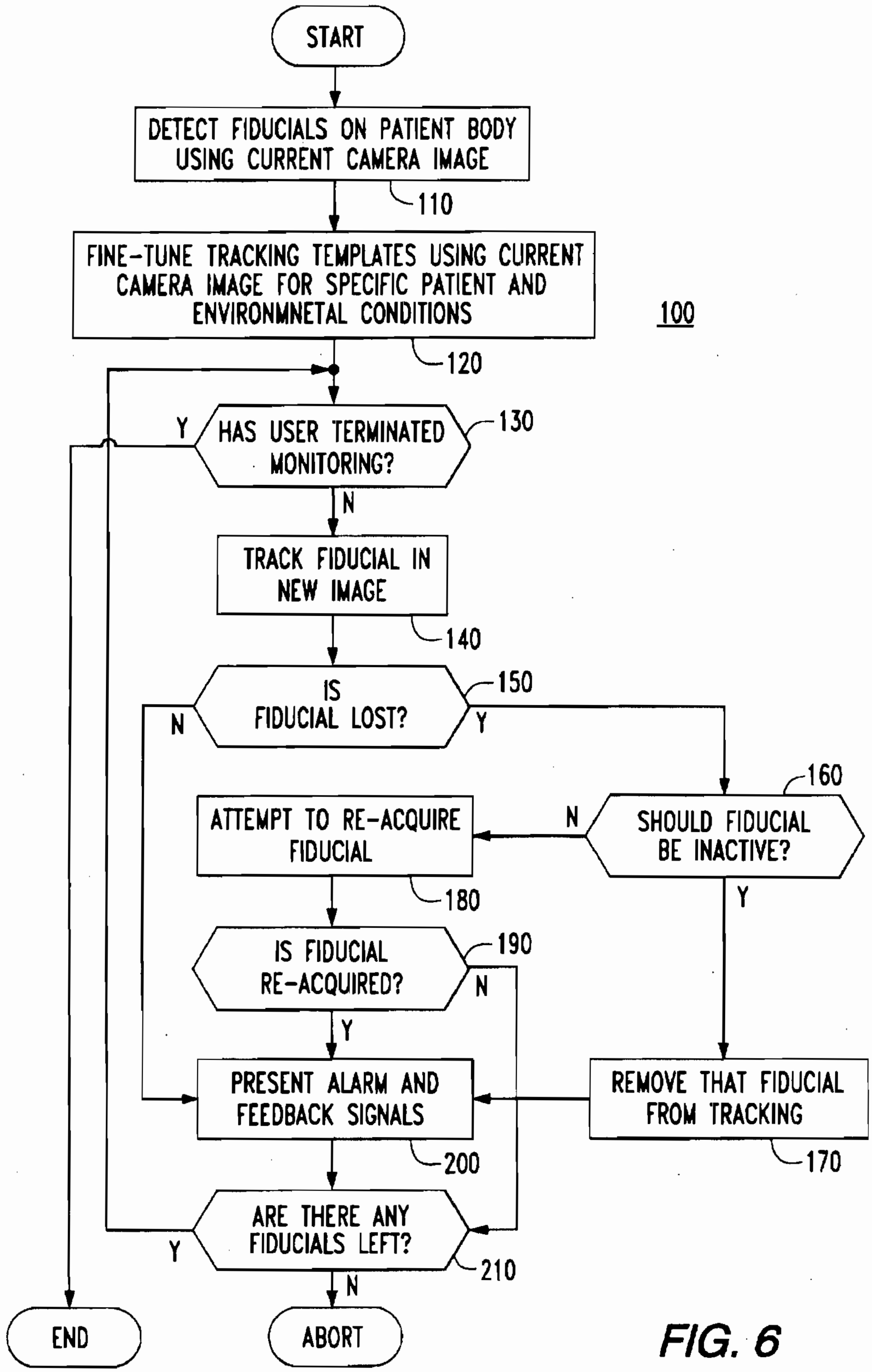
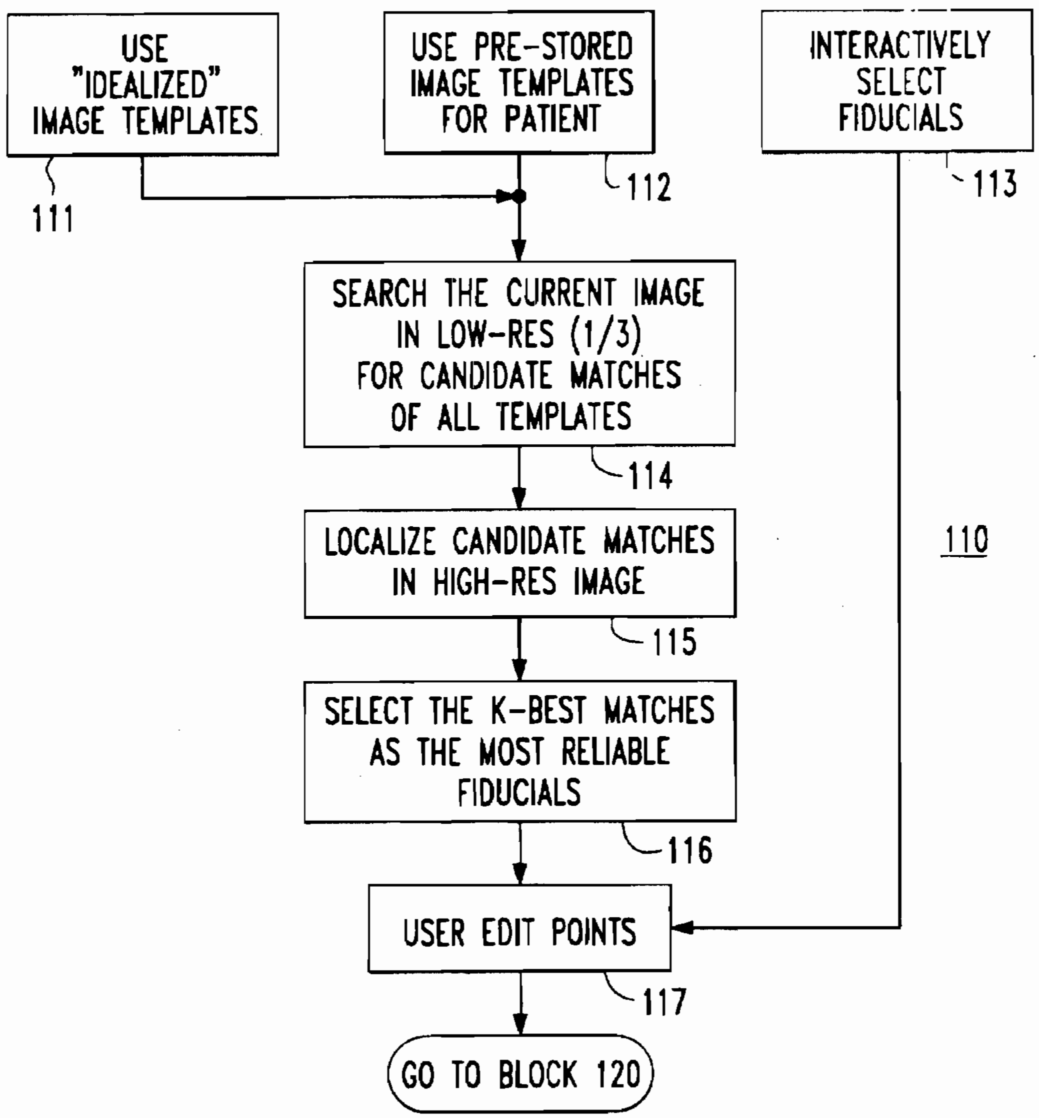

73
81
77
79
81

FIG. 17



START
DETECT FIDUCIALS ON PATIENT BODY USING CURRENT CAMERA IMAGE
110
FINE-TUNE TRACKING TEMPLATES USING CURRENT CAMERA IMAGE FOR SPECIFIC PATIENT AND ENVIRONMNETAL CONDITIONS
120
100
HAS USER TERMINATED MONITORING?
130
Y
N
TRACK FIDUCIAL IN NEW IMAGE
140
IS FIDUCIAL LOST?
150
N
Y
SHOULD FIDUCIAL BE INACTIVE?
160
N
Y
ATTEMPT TO RE-ACQUIRE FIDUCIAL
180
IS FIDUCIAL RE-ACQUIRED?
190
N
Y
REMOVE THAT FIDUCIAL FROM TRACKING
170
PRESENT ALARM AND FEEDBACK SIGNALS
200
ARE THERE ANY FIDUCIALS LEFT?
210
Y
N
END
ABORT

FIG. 6



USE "IDEALIZED" IMAGE TEMPLATES
USE PRE-STORED IMAGE TEMPLATES FOR PATIENT
INTERACTIVELY SELECT FIDUCIALS
111
112
113
SEARCH THE CURRENT IMAGE IN LOW-RES (1/3) FOR CANDIDATE MATCHES OF ALL TEMPLATES
114
LOCALIZE CANDIDATE MATCHES IN HIGH-RES IMAGE
110
115
SELECT THE K-BEST MATCHES AS THE MOST RELIABLE FIDUCIALS
116
USER EDIT POINTS
117
GO TO BLOCK 120

FIG. 7

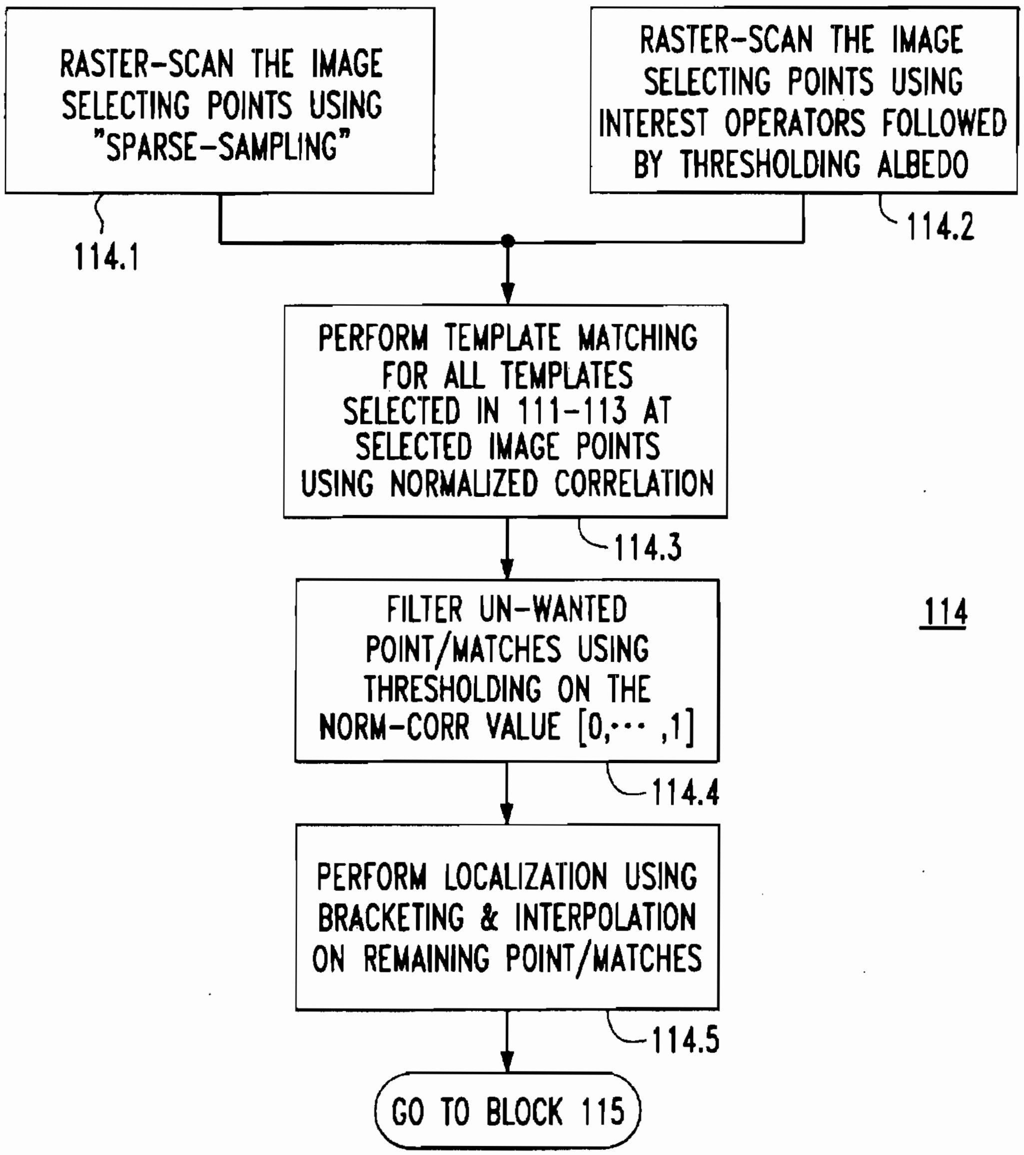

RASTER-SCAN THE IMAGE SELECTING POINTS USING "SPARSE-SAMPLING"
114.1
RASTER-SCAN THE IMAGE SELECTING POINTS USING INTEREST OPERATORS FOLLOWED BY THRESHOLDING ALBEDO
114.2
PERFORM TEMPLATE MATCHING FOR ALL TEMPLATES SELECTED IN 111-113 AT SELECTED IMAGE POINTS USING NORMALIZED CORRELATION
114.3
FILTER UN-WANTED POINT/MATCHES USING THRESHOLDING ON THE NORM-CORR VALUE [0,··· ,1]
114.4
114
PERFORM LOCALIZATION USING BRACKETING & INTERPOLATION ON REMAINING POINT/MATCHES
114.5
GO TO BLOCK 115

FIG. 8

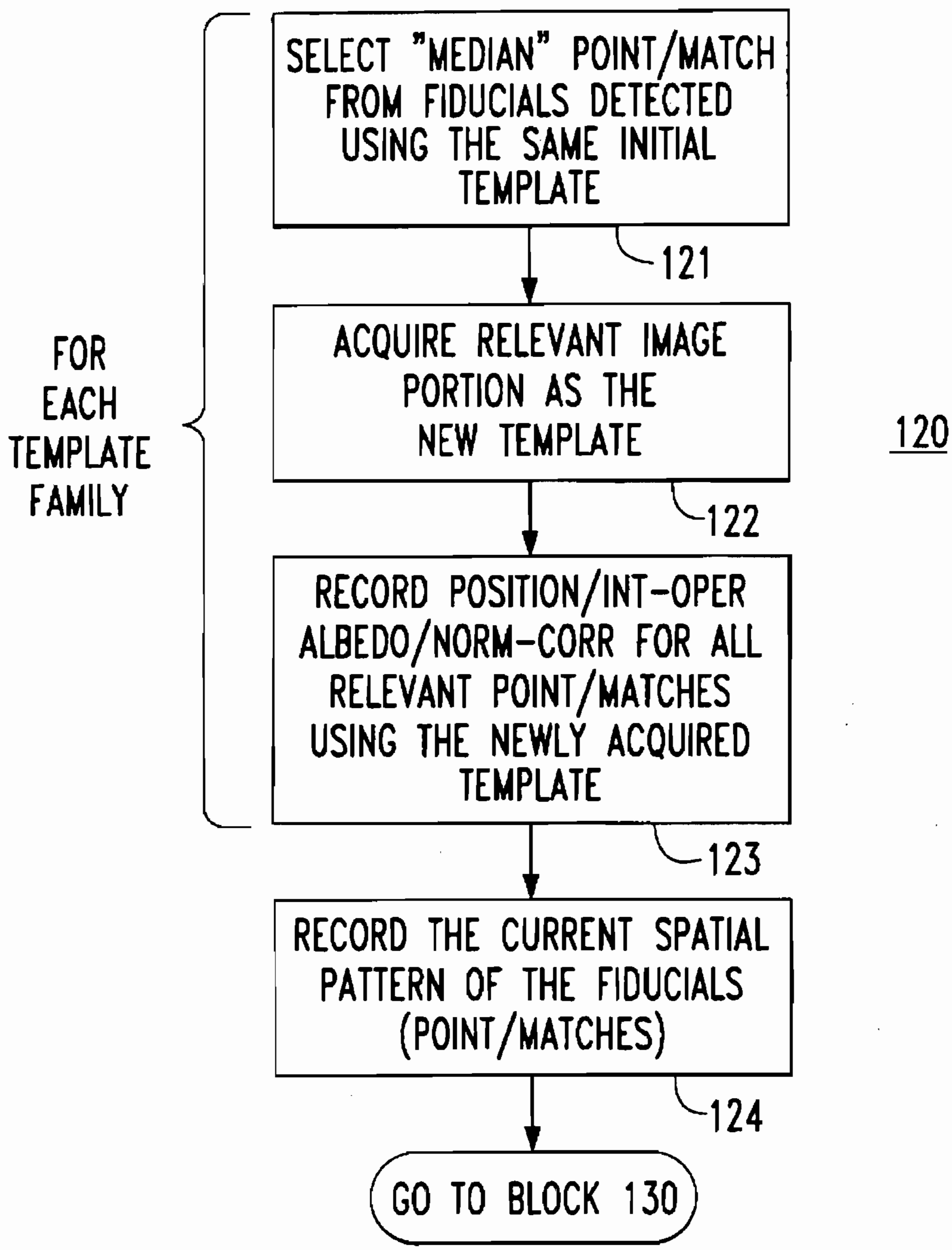

FOR EACH TEMPLATE FAMILY
SELECT "MEDIAN" POINT/MATCH FROM FIDUCIALS DETECTED USING THE SAME INITIAL TEMPLATE
121
ACQUIRE RELEVANT IMAGE PORTION AS THE NEW TEMPLATE
122
RECORD POSITION/INT-OPER ALBEDO/NORM-CORR FOR ALL RELEVANT POINT/MATCHES USING THE NEWLY ACQUIRED TEMPLATE
123
RECORD THE CURRENT SPATIAL PATTERN OF THE FIDUCIALS (POINT/MATCHES)
124
GO TO BLOCK 130
120

FIG. 10

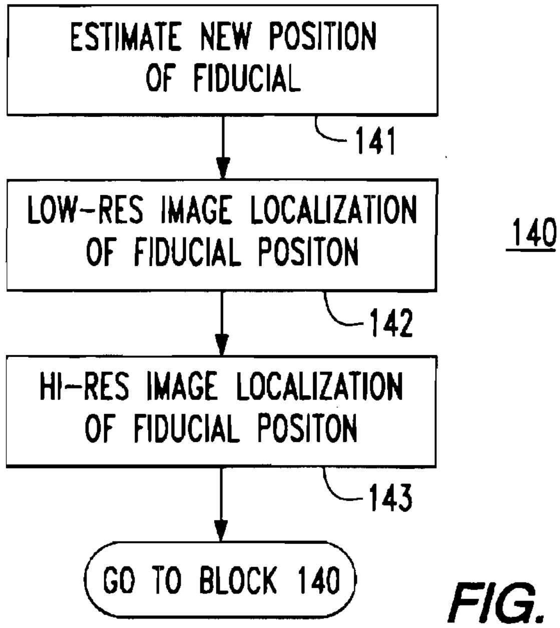

ESTIMATE NEW POSITION OF FIDUCIAL
141
LOW-RES IMAGE LOCALIZATION OF FIDUCIAL POSITON
140
142
HI-RES IMAGE LOCALIZATION OF FIDUCIAL POSITON
143
GO TO BLOCK 140

FIG. 11

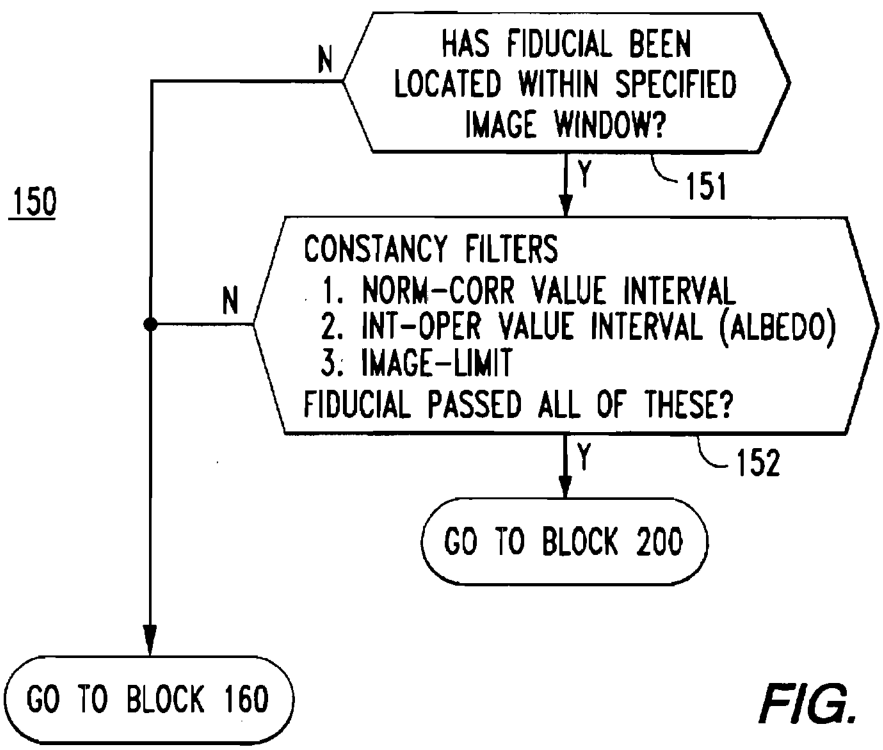

HAS FIDUCIAL BEEN LOCATED WITHIN SPECIFIED IMAGE WINDOW?
N
Y
151
150
CONSTANCY FILTERS
1. NORM-CORR VALUE INTERVAL
2. INT-OPER VALUE INTERVAL (ALBEDO)
3. IMAGE-LIMIT
FIDUCIAL PASSED ALL OF THESE?
N
Y
152
GO TO BLOCK 200
GO TO BLOCK 160

FIG. 14

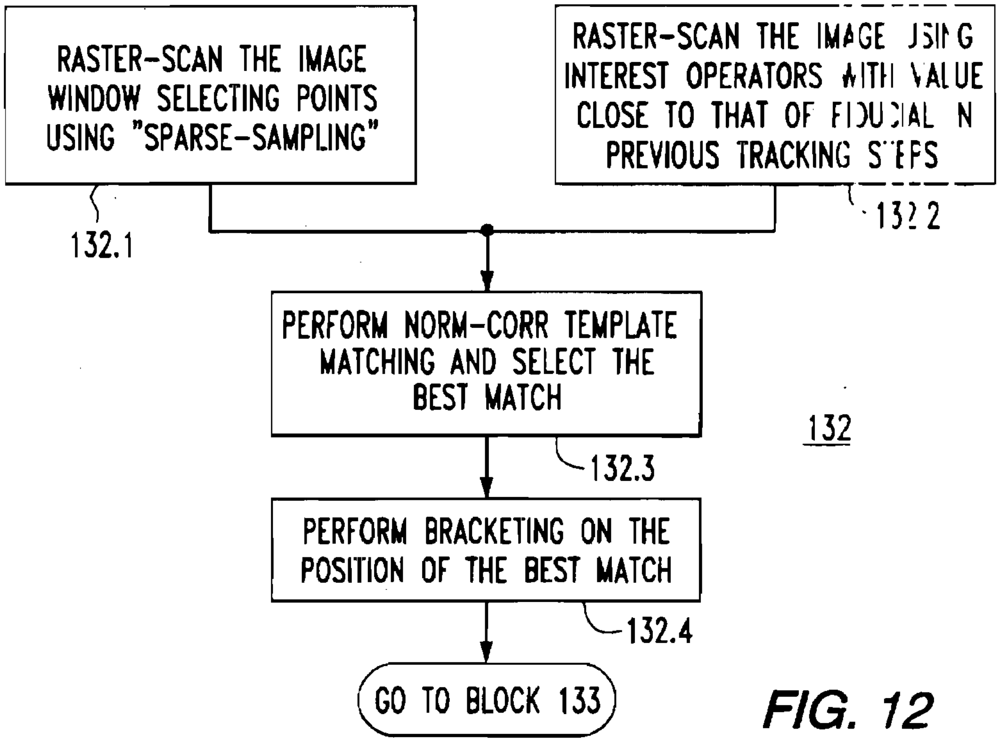

RASTER-SCAN THE IMAGE WINDOW SELECTING POINTS USING "SPARSE-SAMPLING"
132.1
RASTER-SCAN THE IMAGE USING INTEREST OPERATORS WITH VALUE CLOSE TO THAT OF FIDUCIAL IN PREVIOUS TRACKING STEPS
132.2
PERFORM NORM-CORR TEMPLATE MATCHING AND SELECT THE BEST MATCH
132.3
132
PERFORM BRACKETING ON THE POSITION OF THE BEST MATCH
132.4
GO TO BLOCK 133

FIG. 12

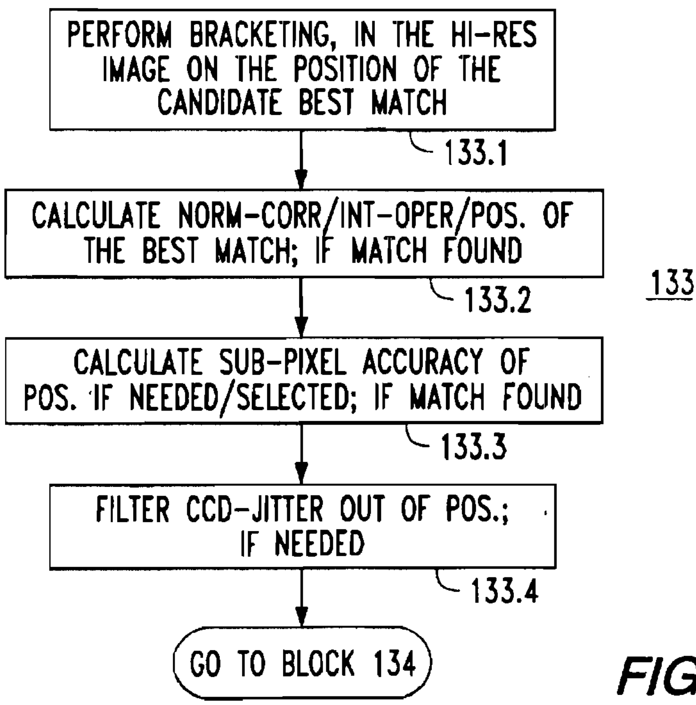

PERFORM BRACKETING, IN THE HI-RES IMAGE ON THE POSITION OF THE CANDIDATE BEST MATCH
133.1
CALCULATE NORM-CORR/INT-OPER/POS. OF THE BEST MATCH; IF MATCH FOUND
133.2
133
CALCULATE SUB-PIXEL ACCURACY OF POS. IF NEEDED/SELECTED; IF MATCH FOUND
133.3
FILTER CCD-JITTER OUT OF POS.; IF NEEDED
133.4
GO TO BLOCK 134

FIG. 13

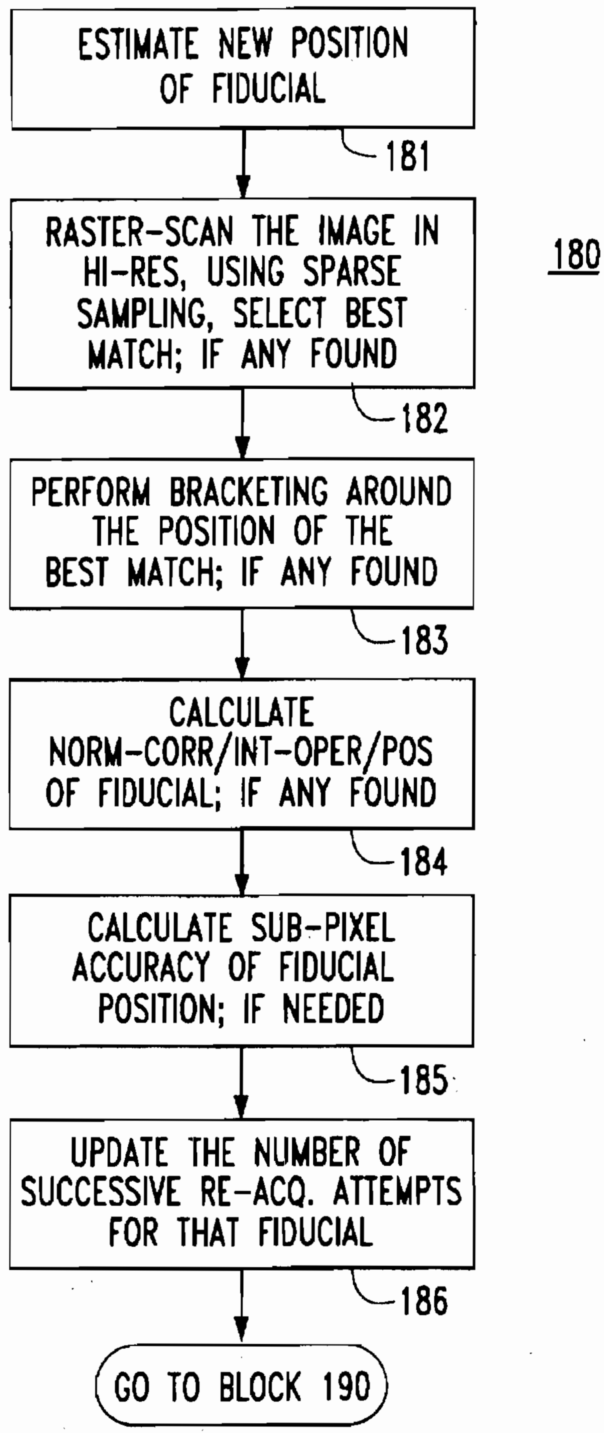

ESTIMATE NEW POSITION OF FIDUCIAL
181
RASTER-SCAN THE IMAGE IN HI-RES, USING SPARSE SAMPLING, SELECT BEST MATCH; IF ANY FOUND
180
182
PERFORM BRACKETING AROUND THE POSITION OF THE BEST MATCH; IF ANY FOUND
183
CALCULATE NORM-CORR/INT-OPER/POS OF FIDUCIAL; IF ANY FOUND
184
CALCULATE SUB-PIXEL ACCURACY OF FIDUCIAL POSITION; IF NEEDED
185
UPDATE THE NUMBER OF SUCCESSIVE RE-ACQ. ATTEMPTS FOR THAT FIDUCIAL
186
GO TO BLOCK 190

FIG. 15

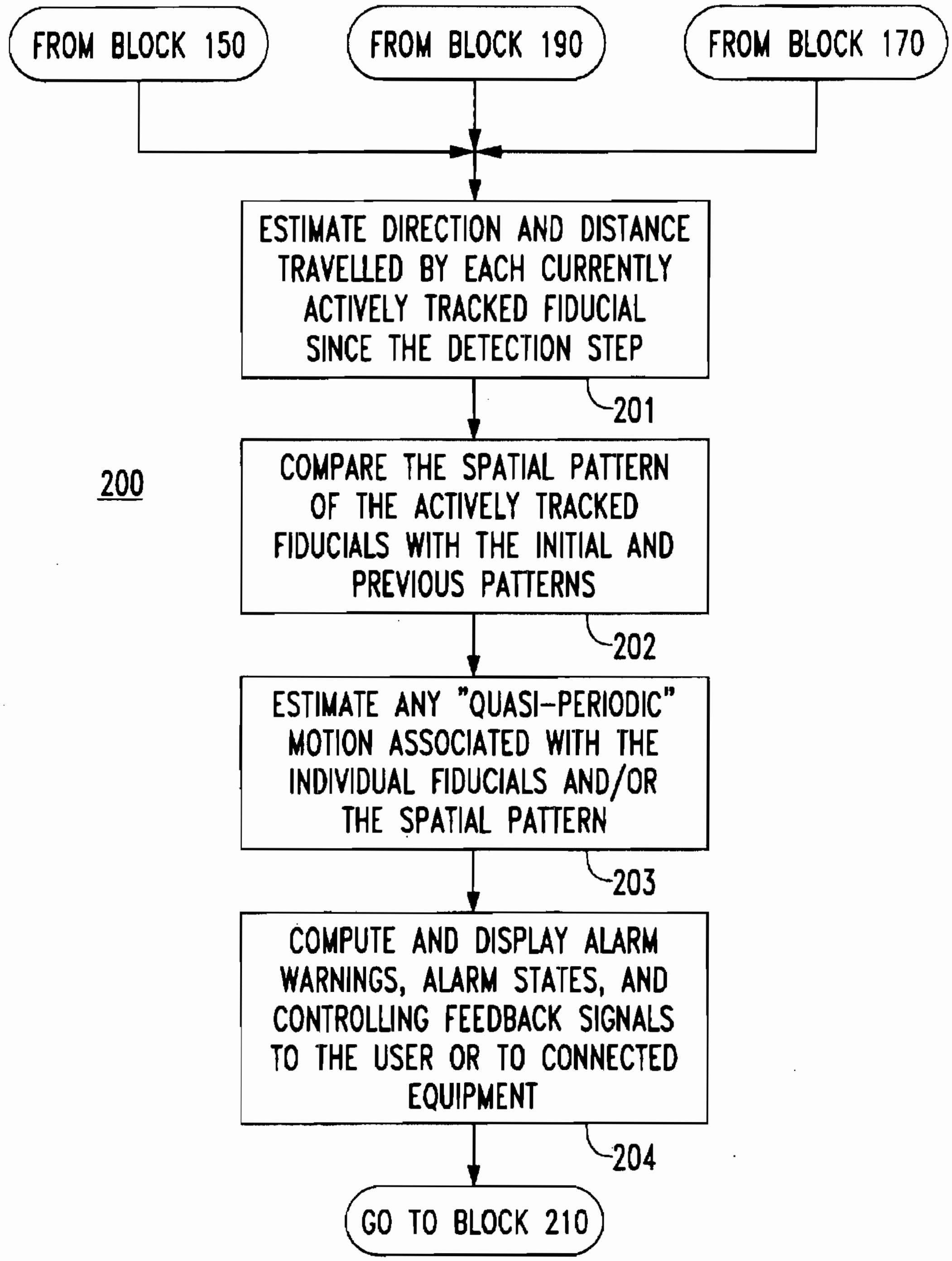

FROM BLOCK 150
FROM BLOCK 190
FROM BLOCK 170
ESTIMATE DIRECTION AND DISTANCE TRAVELLED BY EACH CURRENTLY ACTIVELY TRACKED FIDUCIAL SINCE THE DETECTION STEP
201
200
COMPARE THE SPATIAL PATTERN OF THE ACTIVELY TRACKED FIDUCIALS WITH THE INITIAL AND PREVIOUS PATTERNS
202
ESTIMATE ANY "QUASI-PERIODIC" MOTION ASSOCIATED WITH THE INDIVIDUAL FIDUCIALS AND/OR THE SPATIAL PATTERN
203
COMPUTE AND DISPLAY ALARM WARNINGS, ALARM STATES, AND CONTROLLING FEEDBACK SIGNALS TO THE USER OR TO CONNECTED EQUIPMENT
204
GO TO BLOCK 210

FIG. 16

APPARATUS RESPONSIVE TO MOVEMENT OF A PATIENT DURING TREATMENT/ DIAGNOSIS

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to medical use of radiation for treatment and diagnosis, and more particularly to detection and response to patient movement during radiological treatment and diagnosis.

2. Background Information

Conventional radiotherapy treatment relies on simple patient setup techniques. These techniques use stationary and a limited number of radiation fields, which are often much wider than the tumor or volume, thus effectively compensating for the possibility of a tumor geometric miss. Consequently, a substantial amount of healthy tissue is irradiated and becomes a radio-biological dose limiting factor in tumor control.

Modern conformal dynamic radiotherapy attempts to overcome the above radio-biological limitation by tight-margin conformation of radiation dose distribution tailored to the three-dimensional tumor volume by the use of computer-control multibeam conformal dynamic radio therapy (CCRT). Consequently, the accuracy in patient position, knowledge of the movement of a patient including substantial motion of internal organs such as with breathing is of primary importance. In addition to patient movement which would cause the tight beam to miss the tumor, it is important to be able to detect patient movement which could cause a collision between the patient and the linear accelerator, which is repeatedly repositioned to establish the multiple treatment beams.

There is a need therefore for apparatus for detecting patient movement on radiological treatments/diagnostic equipment.

There is a particular need for such apparatus which can detect submillimeter patient movement in real time.

There is also a need for such apparatus which can detect patient movement initiated from various treatment positions.

There is also a need for such apparatus which can detect patient movement under varying lighting conditions.

There is a further need for such apparatus which can discriminate movement associated with patient breathing from other movement and accommodate therefor.

SUMMARY OF THE INVENTION

These needs and others are satisfied by the invention which is directed to apparatus responsive to movement of a patient which identifies and tracks movement of at least one passive fiducial on the patient. The apparatus applies multiple levels of filtering which can include: correlation, preferably normalized correlation, sparse sampling, bracketing and interpolation, and minima suppression to rapidly identify the location of the at least one fiducial. The multiple levels of filtering are applied at multiple levels of resolution of the digital image signals.

Interest operators can be used in combination with templates to locate the positions of the passive fiducials. The templates can be selected interactively by a user from a display generated by the digital image signals. Alternatively, the template used for tracking is selected from images generated using an initial template. Rather than using the image which best matches the initial template, the template with a median match is selected.

As another aspect of the invention, the means generating an output includes means indicating movement of the at least one passive fiducial relative to at least one selected level of displacement. Preferably, the output means generates a warning that movement exceeds a first displacement and includes means providing a signal for terminating radiation treatment when the movement exceeds a second greater displacement. Preferably, the means providing an indication of movement includes a display generating an image of the patient and the fiducials, together with an indication of movement relative to the first and second displacements.

As yet another aspect of the invention, the means determining movement of the passive fiducials includes means detecting movement associated with patient breathing and random movement. The movement associated with patient breathing can be used to generate a gating signal synchronized to patient breathing. This gating signal can then be used to actuate the beam generator only during selected parts of the breathing cycle.

BRIEF DESCRIPTION OF THE DRAWINGS

A full understanding of the invention can be gained from the following description of the preferred embodiments when read in conjunction with the accompanying drawings in which:

FIG. 1 is an isometric view of apparatus in accordance with the invention for implementing conformal dynamic radiotherapy.

FIG. 2 is a plan view of a patient reclining on a couch which forms part of the apparatus of FIG. 1 and illustrating the placement of fiducials in accordance with the invention.

FIG. 3 is a perspective view of a preferred fiducial used in implementation of the invention.

FIG. 4 is a functional diagram illustrating implementation of the invention.

FIG. 5 is an illustration of a display which is generated by the apparatus of FIG. 1 in implementation of the invention.

FIGS. 6–16 are flow charts of software used in implementation of the invention.

FIG. 17 is an illustration of an interest operator which can be used in implementation of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. 1 illustrates a radiotherapy treatment system 1 in which the invention is implemented. This system 1 includes a machine 3 having a gantry 5 pivotally mounted on a machine base 7 for rotation about a horizontal axis 9. The gantry 5 has a first arm 11 carrying a collimator 13 which directs a beam of high energy radiation 15, such as a beam of high energy photons, along a path which is perpendicular to and passes through an extension of the axis of rotation 9. This intersection is referred to as the isocenter 17. In some machines, a portal imager 19 is mounted on a second arm 21 on the opposite end of the gantry in alignment with the radiation beam 15. The portal imager 19 records radiation which is not absorbed by the patient.

The isocenter 17 serves as the origin of a coordinate system for room space. As can be seen, the X axis coincides with the axis of rotation 9 of the gantry. Thus, as the gantry 5 rotates it defines a plane of treatment containing the Y and Z axes.

The machine 3 further includes a patient positioning assembly 23, which includes a couch 25 mounted on a

support 27 for vertical, lateral and longitudinal movement relative to the support. The support 27 is mounted on a turntable 29, which has its axis 31 vertically aligned under the isocenter 17 and concentric with the Z axis. With this arrangement, the patient positioning assembly 23 has four degrees of freedom: translation in the X, Y and Z axes of room space and rotation about the Z axis. Thus, the patient is not rotated about the longitudinal axis of the couch or tilted about a horizontal axis extending transversely through the couch. However, with the addition of rotation of the gantry in the Y-Z treatment plane, the radiation beam 15 can be directed through a patient reclining on the couch 25 in any desired direction. A computer 33 controls movement of the patient positioning assembly 23 and the gantry 5 for establishing the progression of high energy treatment beams used in practicing conformal radiation therapy.

As previously discussed, in conformal radiation therapy the beam 15 is tightly conformed by the collimator 13 to the specific tumor to be treated. Thus, movement of the patient on the couch 25 of the patient position assembly 23 can cause misalignment of the radiation beam 15 with the tumor. This not only degrades treatment of the tumor but also exposes surrounding healthy tissue to unwanted levels of radiation. In addition, normal breathing by the patient can cause movement of internal organs by an amount which would result in misalignment of the beam. For instance, a tumor on the lower portion of the lung can move several centimeters during normal breathing. Slight movement of the patient can be tolerated; however, treatment should be terminated if acceptable tolerances of movement are exceeded. Furthermore, excessive movement by the patient can also cause a collision between the patient and the gantry as the patient positioning assembly 23 and gantry are positioned for successive treatment beams.

The invention employs a vision system 34 to measure and respond to patient movement. The vision system 34 includes at least one video camera 35. Preferably, multiple cameras are used. In the exemplary embodiment of the invention a first camera 35_1 is mounted on the first arm 11 of the gantry 5 adjacent the collimator 13 and is aimed to capture an image of a patient 37 positioned on the couch 25, as shown in FIG. 2. As the camera 35_1 will be below the couch 25 for some positions of the gantry 5, a second camera 35_2 is fixed to the ceiling over the patient positioning assembly 23. The field of view of this camera 35_2 will be blocked when the gantry 5 is at the top of its arc. Thus, the patient is visible to at least one camera 35 at all times. Additional cameras 35 could be provided, such as cameras laterally displaced from the patient positioning assembly 23 to provide more sensitivity to movement along the axis of, for instance, the camera 35_2. However, as will be discussed below, a single camera can detect three-dimensional movement, including movement toward and away from the camera which is detected as a change in the size of the image.

In the exemplary embodiment of the invention, natural or artificial fiducials are used to detect patient movement. Natural fiducials could be scars or other prominent features of the patient. The preferred fiducial 39 shown in FIG. 3 is a sphere 41 covered with a material having a lambertian surface. Such a surface is highly reflective under low light conditions, yet provides a uniform scattered reflection with no highlights. The sphere 41 is attached to the center of a non-reflective base 43 which is secured to the patient's skin, such as by an adhesive.

In principle, only one fiducial 39 is required. As a practical matter, it is advantageous to provide multiple fiducials placed on the patient so as to detect any movement of the

critical locations. Thus, as shown in FIG. 2, by way of example, four fiducials 39 are placed on the patient's chest. Natural skin markings could be used in addition to the artificial fiducials shown in FIG. 3. If more than one camera 35 is used, each tracks as many of the fiducials 39 as it can see.

FIG. 4 is a functional diagram of the invention. The camera(s) 35 capture an image of the fiducials 39 on the patient 37 reclining on the patient positioning assembly 23. The image captured by the camera 35 is digitized by digitizer 45 to generate digital image signals. These digital image signals are 0 to 255 gray scale signals for each camera pixel. The digital image signals are processed by a processor which includes a patient motion detector 47. Patient motion detector 47 is implemented in the computer 49 shown in FIG. 1. The computer 49 includes a monitor 51 which generates a display 53, an example of which is shown in FIG. 5. The man machine interface 55 for the computer 49 includes a keyboard 57 and a pointing device 59, such as a mouse or trackball.

As will be discussed fully, the patient motion detector 47 detects and identifies the fiducials 39 and then tracks their movement. Movement within a certain narrow tolerance is acceptable, while larger movements are unacceptable. Visible and/or audio warnings of these two classifications of movement can be generated. A gating signal generator 61 responds to unacceptable movement to disable the beam generator 63. This unacceptable movement which would terminate the radiation beam can be movement which displaces the target tumor so that it is missed by the radiation beam, or could be movement which would cause a collision between the patient and the gantry 5 during movement of the machine from one treatment beam to the next. In the former case, the gating signal generator 61 could re-enable the beam generator, if the patient returns to the proper position. For instance, a large sigh could temporarily displace the target area by an unacceptable amount. In accordance with another aspect of the invention, the patient motion detector 47 can track patient breathing and extract such quasi-periodic motion from random patient motion. Gating of the beam generator can then be synchronized with patient breathing. For instance, a tumor on the lung could move up to 4 to 5 centimeters during patient breathing. This is an unacceptable amount of movement. However, by synchronizing generation of the radiation beam with breathing, the tumor can be repetitively irradiated at a fixed position during the breathing cycle.

As shown in FIG. 5, the display 53 presents an image of the patient 37 with the fiducials 39 appearing prominently. An indicator 65, such as the square shown, surrounds each fiducial and is color coded to indicate the state of motion of the fiducial. The fiducial with the largest displacement such as 39*a* is singled out by a distinctive marker, such as a red square 65*a*, while the remaining markers are green squares in the exemplary system. The display also includes a traffic light 67 having a green section 67*g*, a yellow section 67*y* and a red section 67*r*. When motion of the fiducials is within preferred tolerances, the green section 67*g* of the traffic light is on. For motion which is outside the normal range, but which is still acceptable, the yellow section 67*y* is on. The traffic light turns red when the motion of any of the fiducials is approaching the unacceptable. A scale 69 along the side of the display 53 indicates in bar graph form the percentage of maximum allowable displacement of the fiducial of maximum displacement. Thus, for instance, if the red light 67*r* is illuminated and the bar graph 71 indicates 80%, the fiducial with maximum displacement has moved by a distance which

is four fifths of the way through the acceptable displacement. The green, yellow and red regions need not be equal as shown in the example.

Detection of motion of a patient using passive fiducials requires an implementation which is robust enough to accommodate for the variations in the shapes, appearance and lighting conditions to which the fiducials are subjected and, at the same time, is fast enough to provide real time tracking of patient movement. The invention satisfies these requirements by utilization of successive levels of filtering and templates which are modified to accommodate for actual conditions. The result is a system which can track patient movement at 20 Hz or better.

Flow charts of suitable software **100** for implementing the invention are illustrated in FIGS. **6–16**. FIG. **6** illustrates the main routine of the software **100** and includes detecting fiducials on the patient's body is in the current camera image at **110**. As will be described, this is accomplished utilizing templates. The templates are then fine tuned at **120** for the specific patient and environmental conditions. As long as the user desires monitoring as determined at **130**, a loop is entered in which each individual fiducial is tracked as indicated at **140**. It is possible that a fiducial can be lost by the tracking system. This could occur, for instance, if the patient moves so that a fiducial is blocked from the camera's view, or the patient moves a hand through the line of sight of the camera. Also, a fiducial may be temporarily lost by rapid movement or adverse lighting conditions. If a fiducial is lost, as determined at **150**, a number of attempts can be made to reacquire it. If the fiducial is not reacquired within a reasonable time, however, it is removed from tracking as indicated by **160** and **170**. If the selected number of attempts to reacquire, such as for example, five, have not been reached, an attempt is made to reacquire the fiducial at **180**. If the fiducial is reacquired at **190**, then a routine is run at **200** to generate any alarm if needed, and gating signals for the accelerator or beam generator **63** as indicated at **200**. As long as any fiducials remain to be tracked as indicated at **210**, the tracking loop is repetitively run.

FIG. **7** illustrates the general routine **110** for detecting the fiducials **39** in the image represented by the digital image signals. As mentioned, templates are used to identify the locations of the fiducials. The templates indicate what the pattern of digital signals representing the fiducial should look like. The size of the templates used must be considered. Larger templates improve the accuracy but take longer to process. In the exemplary system, templates 40 pixels square have been utilized. There are several ways in which the templates can be generated. As indicated at **111** in FIG. **7**, idealized image templates can be utilized. In addition to such idealized templates or in place thereof, pre-stored image templates for the patient can be used as indicated at **112**. Such pre-stored templates are used, for instance, for natural fiducials such as scars. One template is used for each family of fiducials. For instance, if all of the fiducials are the preferred fiducials such as shown in FIG. **3**, only one template is required because all of the fiducials in the family will generate a similar image.

In addition, templates can be selected interactively by the user at **113**. This is accomplished by using the mouse or trackball **59** to click on the center of a representation of the fiducial on the display **53**.

Where the idealized or pre-stored templates are utilized, a multiresolution pyramid is used to locate the fiducials in the image using the templates. Thus, as indicated at **114**, a search is made of the current image in low resolution for candidate matches of all template families. In the exemplary embodiment of the invention, one-third resolution is used at this point. Matches are made using a normalized correlation between the template and the image. The matches found in low resolution are then verified and localized in high resolution at **115**. The K best matches are then selected as the most reliable fiducials at **116** where K equals the number of fiducials to be tracked. The user is then given the opportunity at **117** to edit the detected location of fiducials found either through use of the idealized or pre-stored templates or templates generated interactively.

The details of the low resolution detection routine performed in block **114** of FIG. **7** is shown in FIG. **8**. As shown at **114.1**, the image can be raster scanned selecting points using sparse sampling. In raster scanning pixels are considered successively along each line, line-by-line in increments of one, while in sparse sampling the increment is greater than one. Alternatively, the image can be raster scanned as indicated at **114.2**, selecting candidate points using interest operators followed by thresholding. Interest operators are simple patterns which emphasize gray scale characteristics of a particular fiducial. An example is shown in FIG. **17**, where the fiducial is a light circle **73** on a dark background **75**. The interest operator **77** could be, for instance, the one pixel value **79** in the center having a gray scale value matching that of the light circle **73**, and the four pixels **81** at the cardinal points having gray scale values similar to that of the background **75**. Such interest operators permit rapid searching of the image and should be selected as to assure identifying all of the fiducials in the family. They will most likely also generate additional candidate points. Returning to FIG. **8**, the interest operator generated value in the exemplary system is the relative albedo. The relative albedo of each point in the low resolution scan is compared to a threshold value to select candidate points.

For each candidate point, a template matching is performed at 114.3, using a normalized correlation. Unwanted point matches are then filtered out at **114.4** using thresholding on the normalized correlation value. In the exemplary embodiment, a normalized correlation of 0.75 was used as the threshold. Bracketing and interpolation are then used at 114.5 to localize the remaining point/matches. In implementing bracketing, a rectangular image window is selected within which the desired point match will definitely lie. Then by interpolating between the correlation values of points on the border of the selected window along with its center, a new estimate of the location of the point match is calculated. This process is repeated with successively smaller windows centered on the new estimate of the location of the point match until a singular point is reached. In the exemplary system, the interpolation is performed using a two-dimensional Gaussian distribution.

FIG. **9** illustrates the techniques for verifying the candidate matches in high-resolution indicated at **115** in FIG. **7**. Bracketing is performed on the selected matches in high resolution as indicated at **115.1**. These points are then filtered at **115.2** within the same image neighborhood using minima suppression. In implementing minima suppression, for each point which has been a match, an area the size of the template is centered on the point. A point is selected as a further candidate match only if it is the best correlation with the template within the template window.

An important aspect of the invention is the fine tuning of the tracking templates called for at **120** in FIG. **6**. FIG. **10** illustrates the details of fine tuning the templates. As indicated at **121**, the median point/match from fiducials detected using the same initial template is selected. For example, if

there are three point matches for a fiducial family, the match having the middle value of correlation is selected. Notice that the match with the best correlation is not selected as it is likely to eliminate some valid matches. This technique adapts the selection of the template to be used for tracking to the actual conditions existing at the time of the selection. The relevant image portion is then acquired as the new template at 122, and the position, the interest operator value and the normalized correlation for all relevant point/matches using this newly acquired template is then recorded at 123. The steps 121–123 are accomplished for each template family. Then, the current special pattern of all the fiducials determined by the point/matches, is recorded at 124.

The program then enters the tracking loop at block 130 in FIG. 6. The routine for continuous tracking, which is called at 140 in FIG. 6 is illustrated in FIG. 11. The new position of the fiducial is estimated at 131 by projecting a velocity vector calculated from prior positions of the fiducial. Localization of fiducial position is then implemented in low resolution using bracketing and interpolation as indicated at 132. This is followed by high resolution localization of the fiducial position at 133, also using bracketing and interpolation.

The low resolution localization of block 131 is implemented by the routine illustrated in FIG. 12. As indicated at 132.1 points are selected by raster scanning the image window using sparse sampling. If interest operators are used, the interest operators with the value closest to that of the fiducial in the previous tracking step is selected at 132.2. In either case, a best match is selected using normalized correlation template matching at 132.3. This is followed by bracketing on the position of the best match at 132.4.

FIG. 13 illustrates the high resolution localization of fiducials called for in block 133 of FIG. 11. As indicated, bracketing is performed on a candidate with best match in high resolution as indicated at 133.1. If a match is found, the normalized correlation, interest operator value and position of the best match are calculated at 133.2. If desired, the sub-pixel accuracy of the position can be calculated at 133.3. The same interpolation technique as in bracketing and interpolation, as described above, is used. Alternatively, bilinear interpolation between the surrounding pixel correlation values could be used. Finally, if needed, charge coupled device (CCD) jitter is filtered out of the position at 133.4. In the exemplary system, a low pass filter is used.

The lost fiducial routine 150 in FIG. 6 is shown in FIG. 14. If the tracking routine finds no fiducial within the specified image window at 151, then clearly the fiducial has been lost. Even if a fiducial has been found, confirmation must be made that it is in fact the new position of the fiducial. Hence, a number of constancy tests are applied in 152. For instance, the normalized correlation value and the interest operator value must not change by more than a selected amount, such as, for example, 15%, from the most current values. Also, image limits are applied. For instance, the fiducial should not have changed position by more than a predetermined amount or, if the edge of the image is reached, the position indicated is not accepted as the fiducial may be out of the field of view, although a continued indication that it is at the edge may be presented.

The routine 180 in FIG. 6 for reacquiring the lost fiducial is shown in FIG. 15. First, the new position of the fiducial is estimated at 181 using a larger search window than was used at 141 in FIG. 11. The image window is then raster scanned in high resolution using sparse sampling to select the best match, if any, at 182. Bracketing is then performed

around the position of the best match, if any, at 183. The normalized correlation interest operator albedo and the position of the fiducial best matched is then determined at 184. This is followed by calculation of sub-pixel accuracy, if needed, at 185. Finally, the number of successive attempts to reacquire the fiducial is updated at 186.

FIG. 16 illustrates the routine 200 in FIG. 6 for generating the alarms and gating the accelerator or beam generator. The direction and distance traveled by each currently actively tracked fiducial since the detection step is estimated at 201. The special pattern of the actively tracked fiducials is compared with the initial pattern and previous patterns at 202. Any quasi-periodic motion associated with the individual fiducials and/or the special pattern is predicted at 203 such as by using past data analysis. This would include movement associated with breathing or tremor of the patient. The alarm warnings, alarm states and accelerator gating signals are then computed at 204 for display or for feedback to the equipment, such as the accelerator.

While specific embodiments of the invention have been described in detail, it will be appreciated by those skilled in the art that various modifications and alternatives to those details could be developed in light of the overall teachings of the disclosure. Accordingly, the particular arrangements disclosed are meant to be illustrative only and not limiting as to the scope of invention which is to be given the full breadth of the claims appended and any and all equivalents thereof.

What is claimed is:

1. Apparatus responsive to movement of a patient positioned on a patient positioning assembly during treatment/diagnosis, said apparatus comprising:

camera means generating digital image signals representing an image of at least one passive fiducial having a lambertian surface on said patient; and

processing means comprising means responsive to actual shape, appearance and lighting conditions of said at least one passive fiducial having a lambertian surface in said image represented by said digital image signals to determine successive positions of said at least one passive fiducial having a lambertian surface, means repetitively determining movement of said at least one passive fiducial having a lambertian surface from said successive positions, and means generating an output in response to predetermined values of said movement.

2. Apparatus responsive to movement of a patient positioned on a patient positioning assembly during treatment/diagnosis, said apparatus comprising:

a single camera generating digital image signals representing an image of at least one fiducial on said patient; and

processing means comprising means responsive to actual shape, appearance and lighting conditions of said at least one fiducial in said image represented by said digital image signals to determine successive positions of said at least one fiducial, means tracking three-dimensional movement of said at least one fiducial from said successive positions and means generating an output in response to predetermined values of said movement.

3. The apparatus of claim 2, wherein said means repetitively determining movement of said at least one fiducial includes means detecting movement associated with patient breathing, and said output means comprises means generating a gating signal synchronized to said patient breathing.

4. The apparatus of claim 2, wherein said processing means comprises means repetitively applying multiple lev-

els of filtering to said digital image signals to determine successive positions of said at least one fiducial.

5. The apparatus of claim 4, wherein said means applying multiple levels of filtering includes means applying bracketing and interpolation to said digital image signals to determine position of said at least one fiducial.

6. The apparatus of claim 4, wherein said means applying multiple levels of filtering includes means applying minima suppression to said digital image signals.

7. The apparatus of claim 4, wherein said means applying multiple levels of filtering include means applying at least two types of filtering selected from a group consisting of correlation, sparse sampling, bracketing and interpolation, and minima suppression.

8. The apparatus of claim 7, wherein said processing means includes means using multiple levels of resolution of said digital image signals to determine successive positions of at least one fiducial and said means applying multiple levels of filtering comprise means applying filtering at each of said multiple levels of resolution.

9. The apparatus of claim 4, wherein said processing means includes means using at least one of templates and interest operators to determine successive positions of said at least one fiducial from said digital image signals.

10. The apparatus of claim 2, wherein said pressing means comprises means using a template to successively determine position of said at least one fiducial and means selecting said template.

11. The apparatus of claim 10, wherein said at least one fiducial comprises a plurality of fiducials, and said means selecting a template includes means generating an initial template, means generating template matches for each of said plurality of fiducials from said digital image signals using said initial template, and means selecting one of said template matches for use in determining positions of each of said plurality of fiducials.

12. The apparatus of claim 11, wherein said means selecting said one of said template matches includes means generating a value for each of said templates matches, and means selecting a template match having a median value as said one template match.

13. Apparatus responsive to movement of a patient positioned on a patient positioning assembly during treatment/diagnosis, said apparatus comprising:

camera means generating digital image signals representing an image of at least one fiducial on said patient; and

processing means comprising means responsive to actual shape, appearance and lighting conditions of said at least one fiducial in said image represented by said digital image signals to determine successive positions of said at least one fiducial at a rate of at least 20 Hz, means tracking movement of said at least one fiducial from said successive positions, and means generating an output in response to predetermined values of said movement.

14. The apparatus of claim 13, wherein said means generating an output includes means generating an indication of movement relative to at least one selected level of displacement.

15. The apparatus of claim 14, wherein said means generating said indication of movement indludes means providing a warning that said movement exceeds a first displacement and means providing a signal for terminating

radiation treatment/diagnosis when said movement exceeds a second displacement greater than said first displacement.

16. The apparatus of claim 14, wherein said means generating an indication of movement comprises display means generating an image of said fiducials and an indication of said movement relative to said first and second displacements.

17. The apparatus of claim 16, wherein said camera means includes means generating digital image signals for a plurality of fiducials, said means repetitively determining movement determines movement of each of said plurality of fiducials, and said display means includes indicator means indicating a fiducial with the greatest movement.

18. The apparatus of claim 14, wherein said means repetitively determining movement includes means detecting movement associated with patient breathing and random movement, and wherein said means generating an indication of movement indicates said random movement.

19. Apparatus responsive to movement of a patient positioned on a patient positioning assembly during treatment/diagnosis, said apparatus comprising:

camera means generating digital image signals representing an image of at least one fiducial on said patient; and

processing means comprising means responsive to actual shape, appearance and lighting conditions of said at least one fiducial in said image represented by said digital image signals to determine successive positions of said at least one fiducial, means repetitively determining movement of said at least one fiducial from said successive positions, and means generating an output in response to predetermined values of said movement;

said processing means further comprising means using a template to successively determine position of said at least one fiducial and means selecting said template comprising display means, means generating on said display means an image of said at least one fiducial from said digital image signals and user interface means for selection of a template from said image of said at least one fiducial.

20. Apparatus responsive to movement of a patient positioned on a patient positioning assembly, said apparatus comprising:

camera means generating digital image signals representative of an image of said patient; and

processing means comprising means determining movement of said patient from said digital image signals, including movement associated with breathing by said patient, and gating means generating gating signals synchronized with said movement associated with breathing by said patient.

21. The apparatus of claim 20, wherein said camera means generates said digital image signals representing an image of at least one fiducial on said patient, and said means determining movement of said patient includes means determining movement of said at least one fiducial.

22. The apparatus of claim 20 adapted for use during treatment of said patient with a radiation beam generated by a beam generator, wherein said gating means comprises means generating said gating signals synchronized to actuate said beam generator in synchronism with patient breathing.

* * * * *

Att. Docket No.: 127442

ASSIGNMENT

In consideration of One Dollar ($1.00) and other good and valuable consideration, the receipt of which is hereby acknowledged, we **Andre M. Kalend, Joel Greenberger, Karun B. Shimoga, Charalambos N. Athanassiou, and Takeo Kanade** citizens, respectively, of Zaire, the United States of America, India, Greece, and Japan residing, respectively, at 103 Trotwood Drive, Monroeville, PA 15146; 749 Chestnut Street, Sewickley, PA 15143; 5030 Centre Avenue, Apt. #560, Pittsburgh, PA 15213; c/o I. Athanassiou, Derigny 8, Athens 10434, GREECE; 130 Penrose Drive., Pittsburgh, PA 15208;

Hereby sell, assign and transfer to the **University of Pittsburgh of the Commonwealth System of Higher Education,** a non-profit Pennsylvania corporation, having a place of business at 911 William Pitt Union, Pittsburgh, Pennsylvania 15260, in the County of Allegheny and Commonwealth of Pennsylvania, its successors, assigns and legal representatives, my/our entire right, title and interest, for all countries, in and to any and all inventions and improvements which are disclosed and claimed, and any and all improvements which are disclosed but not claimed, in United States Patent Application **APPARATUS FOR MATCHING X-RAY IMAGES WITH REFERENCE IMAGES** executed respectively by us on even date herewith and in and to said application and all divisional, continuing, substitute, renewal, reissue and all other applications for Letters Patent which have been or shall be filed on any of said improvements disclosed in said application; and in and to all original and reissued patents which have been or shall be issued on said improvements;

Authorized and request the Commissioner of Patents and Trademarks to issue to said Assignee, the University of Pittsburgh of the Commonwealth System of Higher Education, its successors, assigns and legal representatives, in accordance with this assignment, any and all United States Letters Patent on said improvements, or any of them, disclosed in said application;

Agree that, when requested, without charge to but at the expense of said Assignee, its successors, assigns and legal representatives, to carry out in good faith the intent and purpose of this assignment I/we will, for all countries, execute all divisional, continuing, substitute, renewal, reissue, and all other patent applications on any and all said improvements; execute all rightful oaths and other papers; communicate to said Assignee, its successors, assigns, and representatives, all facts known to me/us relating to said improvements and the history thereof; testify in all legal proceedings; and generally do everything possible which said Assignee, its successors, assigns or representatives shall consider desirable for aiding in securing, maintaining and enforcing proper patent protection for said improvements, and for vesting title to said improvements and all applications for patents and all patents on said improvements, in said Assignee, its successors, assigns and legal representatives;

Covenant with said Assignee, its successors, assigns and legal representatives that I/we have made to others no assignment, grant, mortgage, license or other agreement affecting the rights and property herein conveyed, and that I/we have full right to convey the same as herein expressed.

DATE 10-10-96 ____________________ (SEAL)
ANDRE M. KALEND

Commonwealth of Pennsylvania)
):
County of Allegheny)

Before me this 10th day of October, 1996, personally appeared A. M. Kalend, to me personally known to be the person who is described herein and who executed the above instrument, and he acknowledged to me that he executed the same of his own free will for the purposes herein set forth.

Notarial Seal
Patricia A. Lang, Notary Public
Pittsburgh, Allegheny County
My Commission Expires Nov. 22, 1997
Member, Pennsylvania Association of Notaries

(Affix Seal Here)

Patricia A. Lang
Notary Public

* * *

DATE 10/21/96 ____________________ (SEAL)
JOEL GREENBERGER

State of Pennsylvania)
):
County of Allegheny)

Before me this 21st day of October, 1996, personally appeared Joel Greenberger, MD, to me personally known to be the person who is described herein and who executed the above instrument, and he acknowledged to me that he executed the same of his own free will for the purposes herein set forth.

Notarial Seal
Patricia A. Lang, Notary Public
Pittsburgh, Allegheny County
My Commission Expires Nov. 22, 1997
Member, Pennsylvania Association of Notaries

(Affix Seal Here)

Patricia A. Lang
Notary Public

* * *

DATE Oct 18, 96 ____________________ (SEAL)
KARUN B. SHIMOGA

State of Pennsylvania)
):
County of Allegheny)

Before me this 18th day of October, 1996, personally appeared Karun B. Shimoga, to me personally known to be the person who is described herein and who executed the above instrument, and he acknowledged to me that he executed the same of his own free will for the purposes herein set forth.

Emma Jean Scavincky
Notary Public

(Affix Seal Here)

Notarial Seal
Emma Jean Scavincky, Notary Public
Pittsburgh, Allegheny County
My Commission Expires Dec. 14, 1998
Member, Pennsylvania Association of Notaries

* * *

DATE 9/23/1996 (SEAL)

CHARALAMBOS N. ATHANASSIOU

COUNTRY OF GREECE):

ΕΙΡΗΝΗ Ν. ΑΘΑΝΑΣΙΟΥ
ΔΙΚΗΓΟΡΟΣ
ΔΕΡΙΓΝΥ 8
ΤΗΛ. 82.38.391

Before me this 23 day of September, 1996, personally appeared Charalambos N. Athanassiou to me personally known to be the person who is described herein and who executed the above instrument, and he acknowledged to me that he executed the same of his own free will for the purposes herein set forth.

IRENE N. ATHANASSIOU
ATTORNEY AT LAW
LAW-OFFICE
DERIGNY 8 - ATHENS
GR-10434, HELLAS
PHONE/FAX: 8238391

Notary Public
IRENE N. ATHANASSIOU

ΕΙΡΗΝΗ Ν. ΑΘΑΝΑΣΙΟΥ
ΔΙΚΗΓΟΡΟΣ
ΔΕΡΙΓΝΥ 8 - ΑΘΗΝΑ 104 34
ΤΗΛ. 82.38.391 - Α.Φ.Μ. 43698514
Δ.Ο.Υ. Β' ΕΛΕΥΘ. ΕΠΑΓ. ΑΘΗΝΑΣ

* * *

DATE Oct 18, 1996 (SEAL)

TAKEO KANADE

Commonwealth of Pennsylvania):

County of Allegheny

Before me this 18th day of October, 1996, personally appeared Takeo Kanade, to me personally known to be the person who is described herein and who executed the above instrument, and he acknowledged to me that he executed the same of his own free will for the purposes herein set forth.

Notary Public

(Affix Seal Here)

Notarial Seal
Emma Jean Scavincky, Notary Public
Pittsburgh, Allegheny County
My Commission Expires Dec. 14, 1996
mber, Pennsylvania Association of Notaries

US005784431A

United States Patent [19]

Kalend et al.

[11] **Patent Number: 5,784,431**

[45] **Date of Patent: Jul. 21, 1998**

[54] **APPARATUS FOR MATCHING X-RAY IMAGES WITH REFERENCE IMAGES**

[75] Inventors: **Andre M. Kalend**, Monroeville; **Joel Greenberger**, Sewickley; **Karun B. Shimoga**, Pittsburgh, all of Pa.; **Charalambos N. Athanassiou**, Athens, Greece; **Takeo Kanade**, Pittsburgh, Pa.

[73] Assignee: **University of Pittsburgh of the Commonwealth System of Higher Education**, Pittsburgh, Pa.

[21] Appl. No.: **739,622**

[22] Filed: **Oct. 29, 1996**

[51] **Int. Cl.**[6] **A61N 5/10**

[52] **U.S. Cl.** **378/65**; 378/69; 378/901

[58] **Field of Search** 378/8, 20, 65, 378/68, 69, 901

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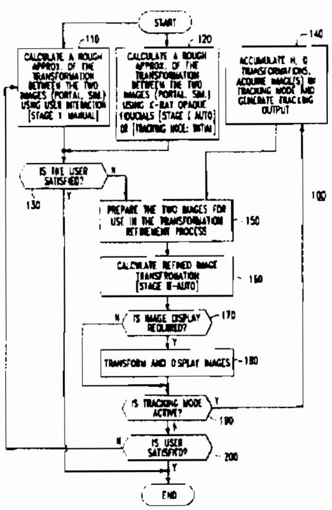
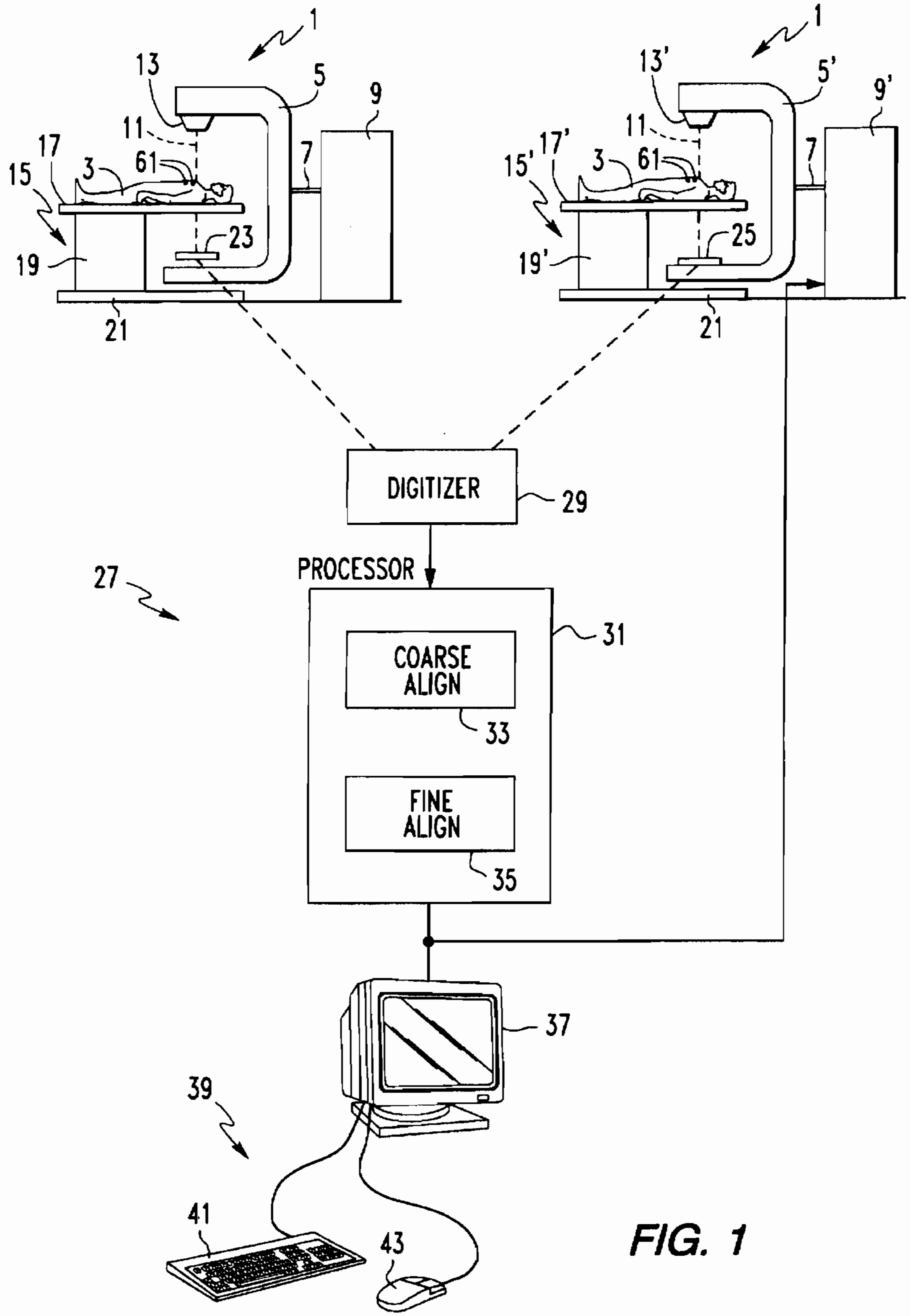
Primary Examiner—David P. Porta
Assistant Examiner—David Vernon Bruce
Attorney, Agent, or Firm—Richard V. Westerhoff; Eckert Seamans Cherin & Mellot, LLC

[57] **ABSTRACT**

X-ray images such as radiotherapy portal images and simulation images are matched by apparatus which digitizes the images and automatically processes the digitized signals to generate matched digitized signals which can be displayed for comparison. The digitized images are first coarse aligned using a transform generated from seed points selected interactively from the two images or through detection and identification of x-ray opaque fiducials placed on the patient. A fine alignment is then performed by first selecting intersecting regions of the two images and enhancing those regions. Secondly, an updated transform is generated using robust motion flow in these regions at successive ascending levels of resolution. The updated transform is then used to align the images which are displayed for comparison. The updated transform can also be used to control the radiotherapy equipment.

28 Claims, 8 Drawing Sheets





1
13
5
9
11
17
15
3
61
7
23
19
21
13'
5'
9'
11
17'
15'
25
19'
DIGITIZER
29
PROCESSOR
27
31
COARSE ALIGN
33
FINE ALIGN
35
37
39
41
43

FIG. 1

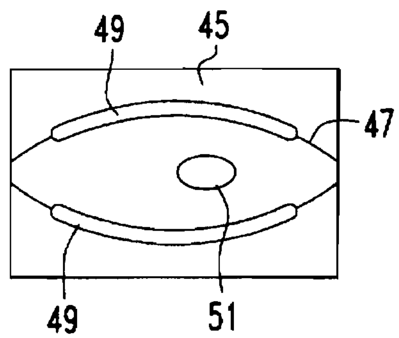


FIG. 2a

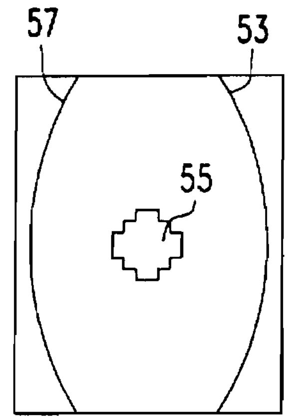


FIG. 2b

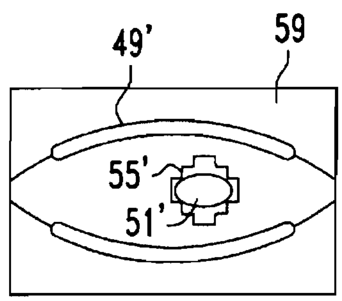
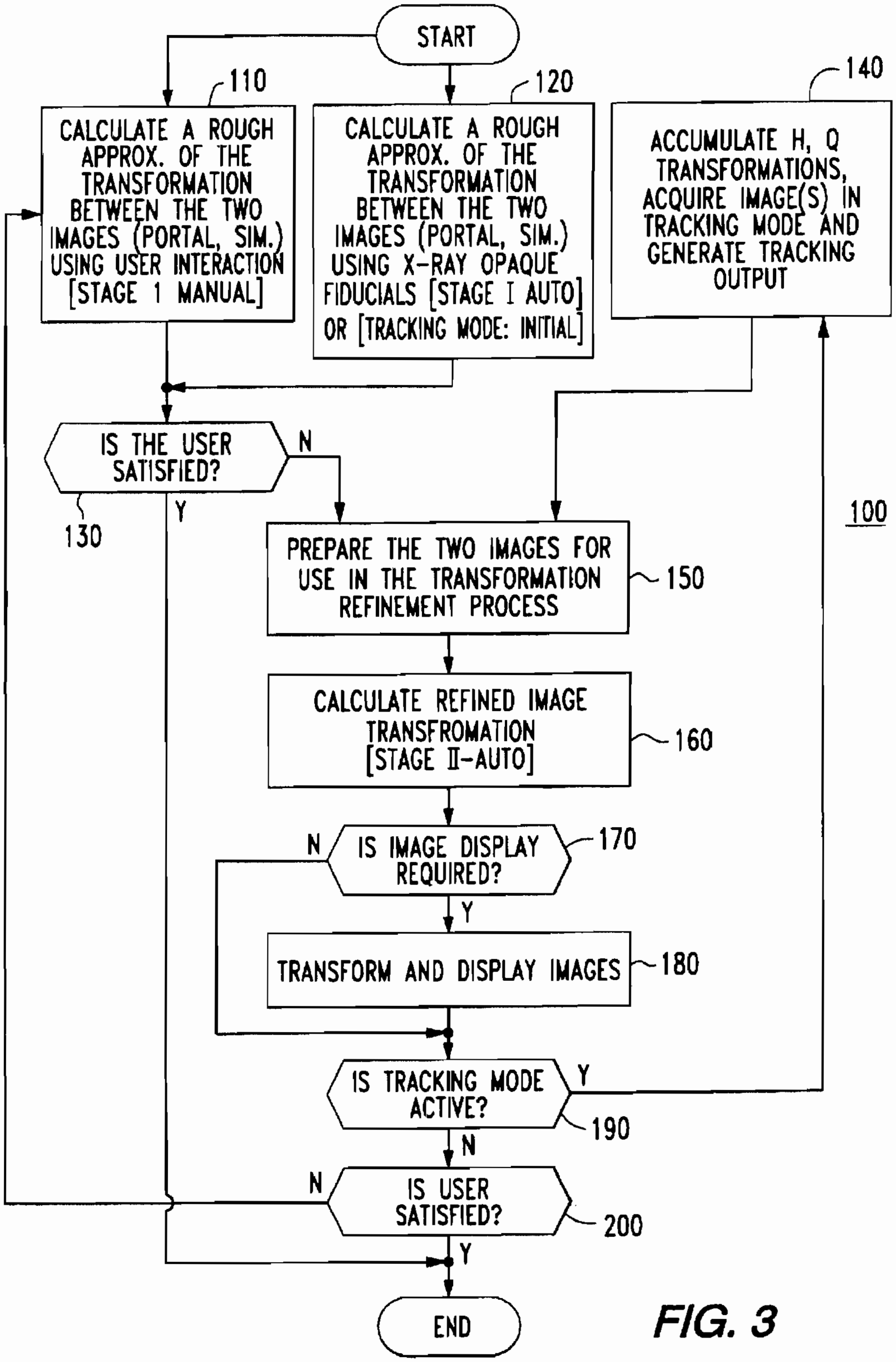


FIG. 2c



START
CALCULATE A ROUGH APPROX. OF THE TRANSFORMATION BETWEEN THE TWO IMAGES (PORTAL, SIM.) USING USER INTERACTION [STAGE 1 MANUAL]
110
CALCULATE A ROUGH APPROX. OF THE TRANSFORMATION BETWEEN THE TWO IMAGES (PORTAL, SIM.) USING X-RAY OPAQUE FIDUCIALS [STAGE I AUTO] OR [TRACKING MODE: INITIAL]
120
ACCUMULATE H, Q TRANSFORMATIONS, ACQUIRE IMAGE(S) IN TRACKING MODE AND GENERATE TRACKING OUTPUT
140
IS THE USER SATISFIED?
N
Y
130
100
PREPARE THE TWO IMAGES FOR USE IN THE TRANSFORMATION REFINEMENT PROCESS
150
CALCULATE REFINED IMAGE TRANSFROMATION [STAGE II-AUTO]
160
IS IMAGE DISPLAY REQUIRED?
170
N
Y
TRANSFORM AND DISPLAY IMAGES
180
IS TRACKING MODE ACTIVE?
Y
190
N
IS USER SATISFIED?
N
200
Y
END

FIG. 3

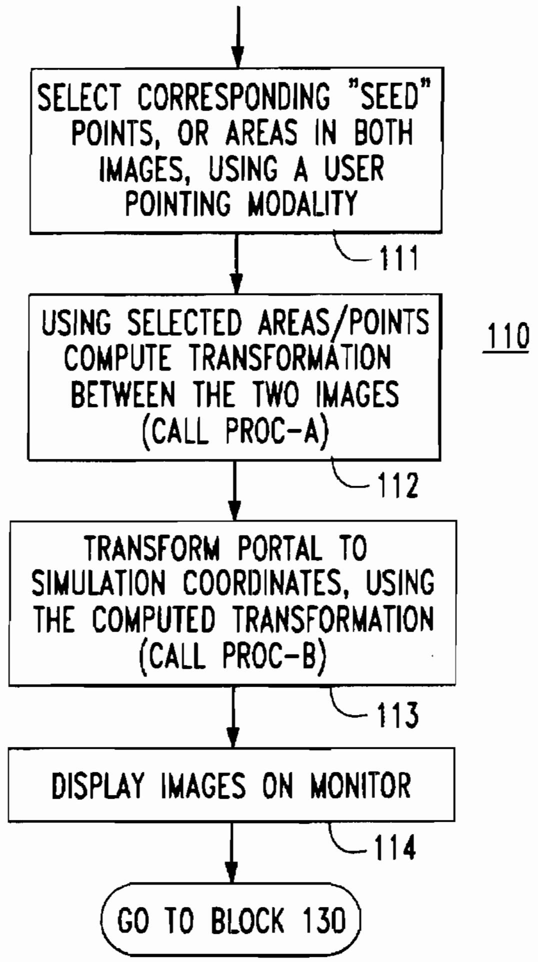

SELECT CORRESPONDING "SEED" POINTS, OR AREAS IN BOTH IMAGES, USING A USER POINTING MODALITY
111
USING SELECTED AREAS/POINTS COMPUTE TRANSFORMATION BETWEEN THE TWO IMAGES (CALL PROC-A)
110
112
TRANSFORM PORTAL TO SIMULATION COORDINATES, USING THE COMPUTED TRANSFORMATION (CALL PROC-B)
113
DISPLAY IMAGES ON MONITOR
114
GO TO BLOCK 130

FIG. 4

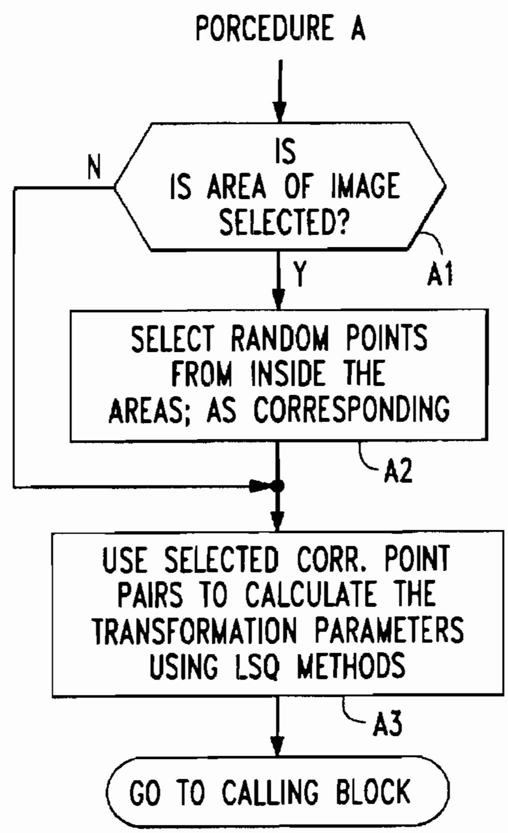

PORCEDURE A
IS
IS AREA OF IMAGE SELECTED?
N
Y
A1
SELECT RANDOM POINTS FROM INSIDE THE AREAS; AS CORRESPONDING
A2
USE SELECTED CORR. POINT PAIRS TO CALCULATE THE TRANSFORMATION PARAMETERS USING LSQ METHODS
A3
GO TO CALLING BLOCK

FIG. 5

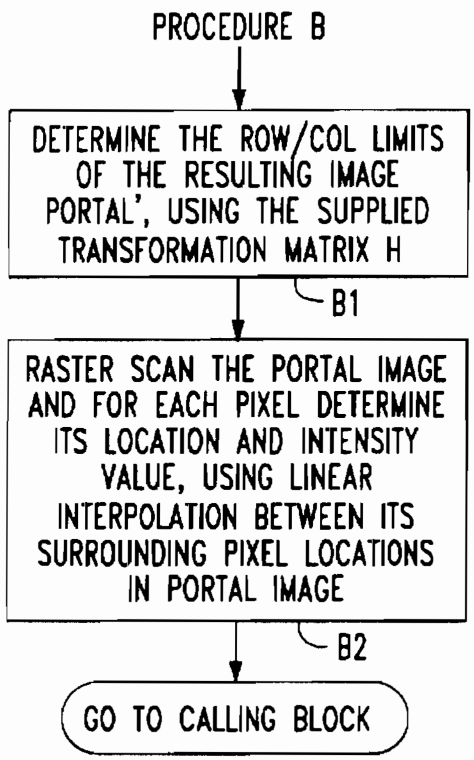

PROCEDURE B
DETERMINE THE ROW/COL LIMITS OF THE RESULTING IMAGE PORTAL', USING THE SUPPLIED TRANSFORMATION MATRIX H
B1
RASTER SCAN THE PORTAL IMAGE AND FOR EACH PIXEL DETERMINE ITS LOCATION AND INTENSITY VALUE, USING LINEAR INTERPOLATION BETWEEN ITS SURROUNDING PIXEL LOCATIONS IN PORTAL IMAGE
B2
GO TO CALLING BLOCK

FIG. 6

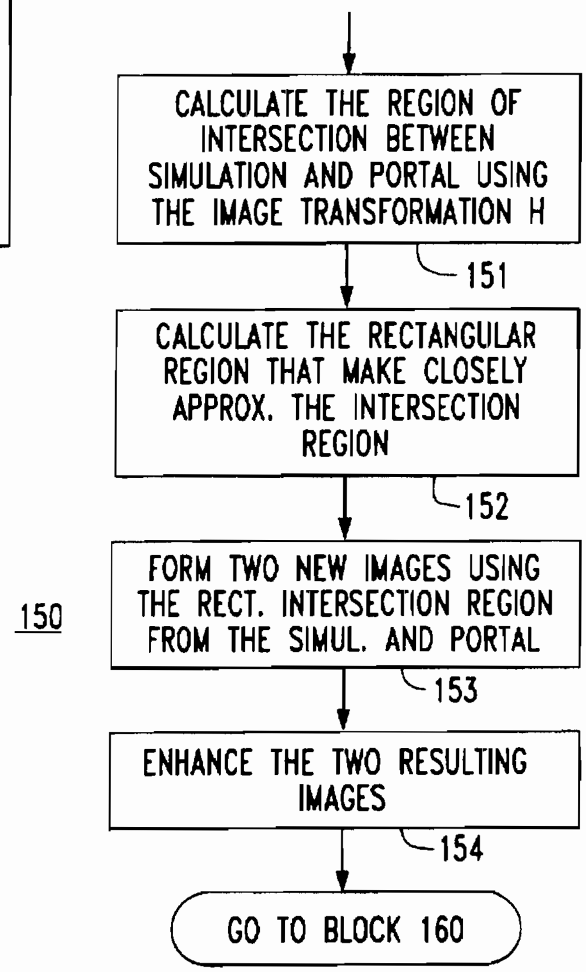
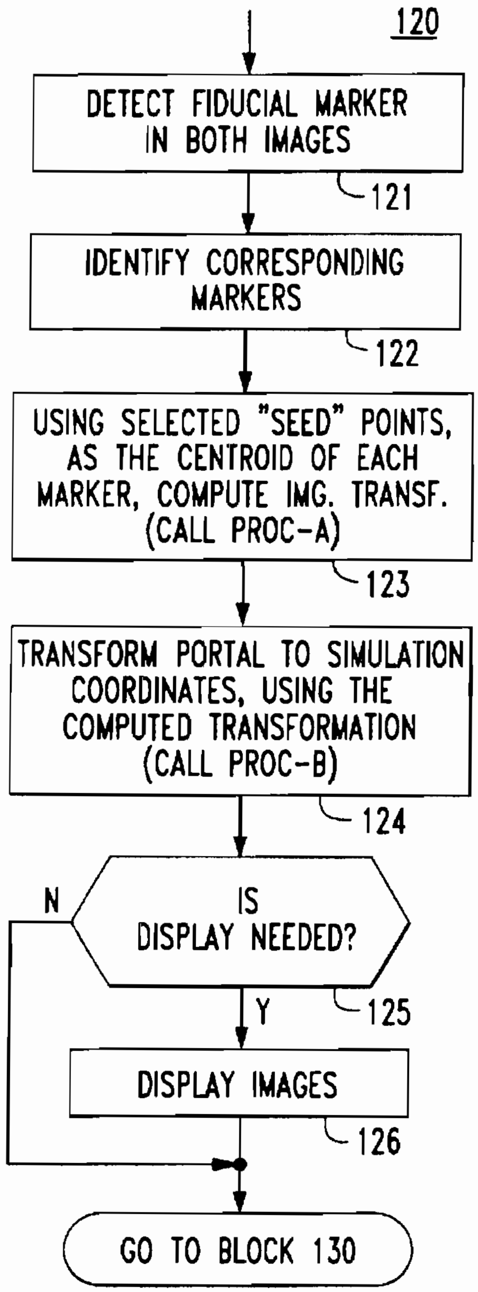
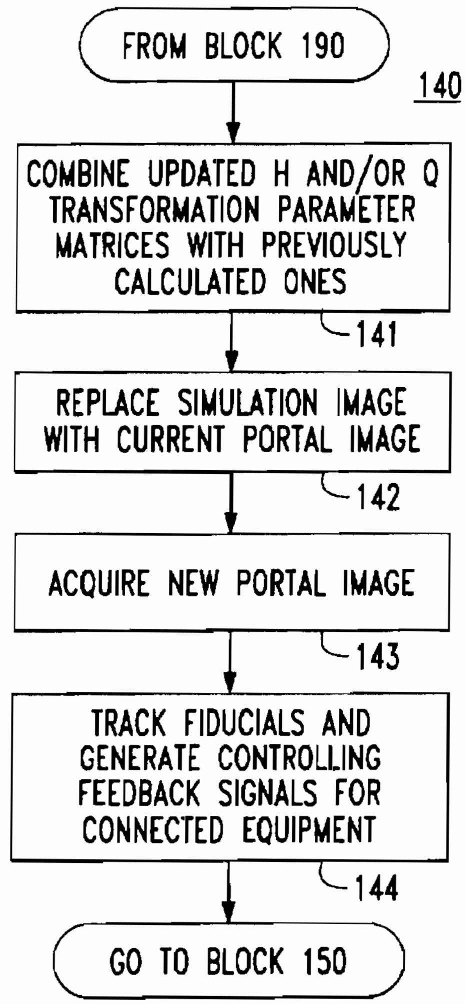

CALCULATE THE REGION OF INTERSECTION BETWEEN SIMULATION AND PORTAL USING THE IMAGE TRANSFORMATION H
151
CALCULATE THE RECTANGULAR REGION THAT MAKE CLOSELY APPROX. THE INTERSECTION REGION
152
150
FORM TWO NEW IMAGES USING THE RECT. INTERSECTION REGION FROM THE SIMUL. AND PORTAL
153
ENHANCE THE TWO RESULTING IMAGES
154
GO TO BLOCK 160

FIG. 8



120
DETECT FIDUCIAL MARKER IN BOTH IMAGES
121
IDENTIFY CORRESPONDING MARKERS
122
USING SELECTED "SEED" POINTS, AS THE CENTROID OF EACH MARKER, COMPUTE IMG. TRANSF. (CALL PROC-A)
123
TRANSFORM PORTAL TO SIMULATION COORDINATES, USING THE COMPUTED TRANSFORMATION (CALL PROC-B)
124
N
IS DISPLAY NEEDED?
Y
125
DISPLAY IMAGES
126
GO TO BLOCK 130

FIG. 7



FROM BLOCK 190
140
COMBINE UPDATED H AND/OR Q TRANSFORMATION PARAMETER MATRICES WITH PREVIOUSLY CALCULATED ONES
141
REPLACE SIMULATION IMAGE WITH CURRENT PORTAL IMAGE
142
ACQUIRE NEW PORTAL IMAGE
143
TRACK FIDUCIALS AND GENERATE CONTROLLING FEEDBACK SIGNALS FOR CONNECTED EQUIPMENT
144
GO TO BLOCK 150

FIG. 11

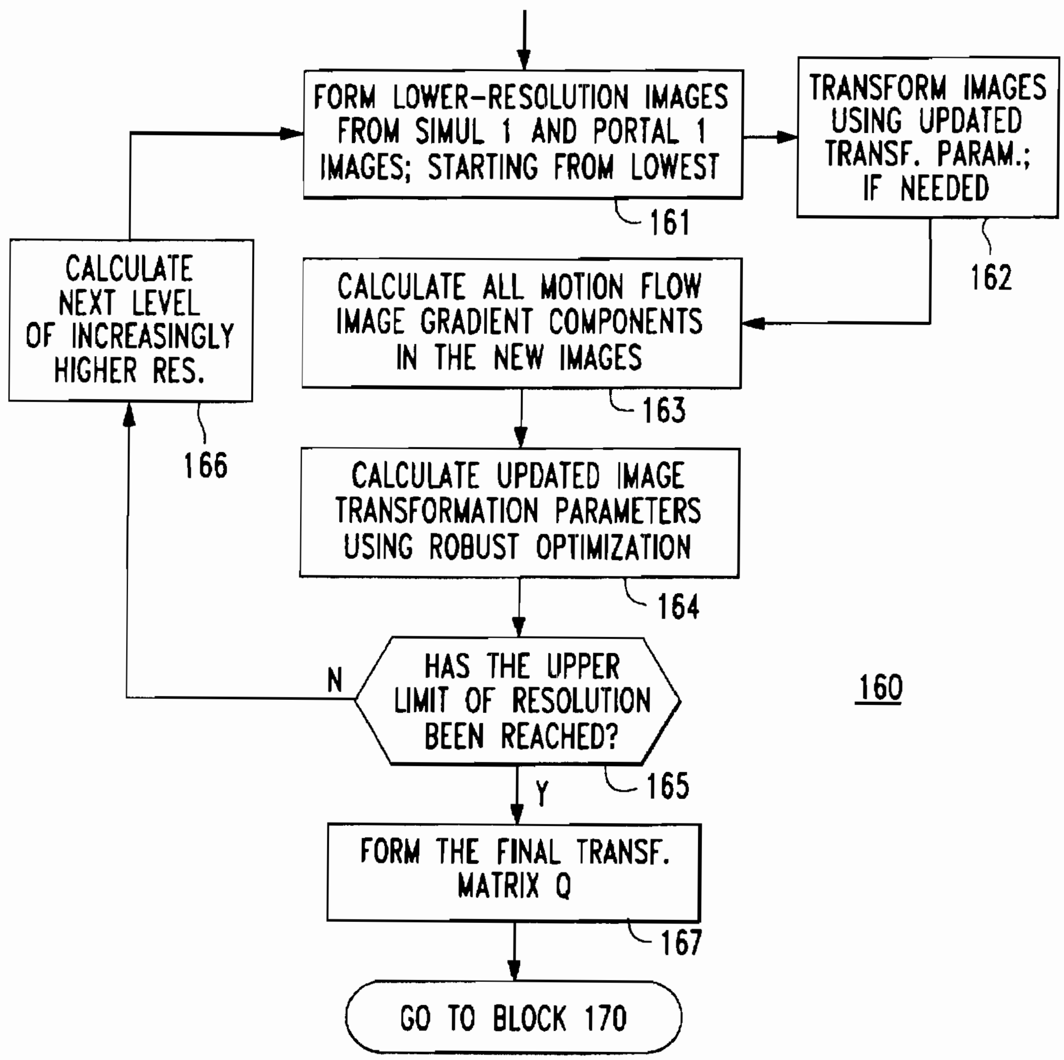

FORM LOWER-RESOLUTION IMAGES FROM SIMUL 1 AND PORTAL 1 IMAGES; STARTING FROM LOWEST
161
TRANSFORM IMAGES USING UPDATED TRANSF. PARAM.; IF NEEDED
162
CALCULATE ALL MOTION FLOW IMAGE GRADIENT COMPONENTS IN THE NEW IMAGES
163
CALCULATE UPDATED IMAGE TRANSFORMATION PARAMETERS USING ROBUST OPTIMIZATION
164
HAS THE UPPER LIMIT OF RESOLUTION BEEN REACHED?
165
N
Y
CALCULATE NEXT LEVEL OF INCREASINGLY HIGHER RES.
166
FORM THE FINAL TRANSF. MATRIX Q
167
GO TO BLOCK 170
160

FIG. 9

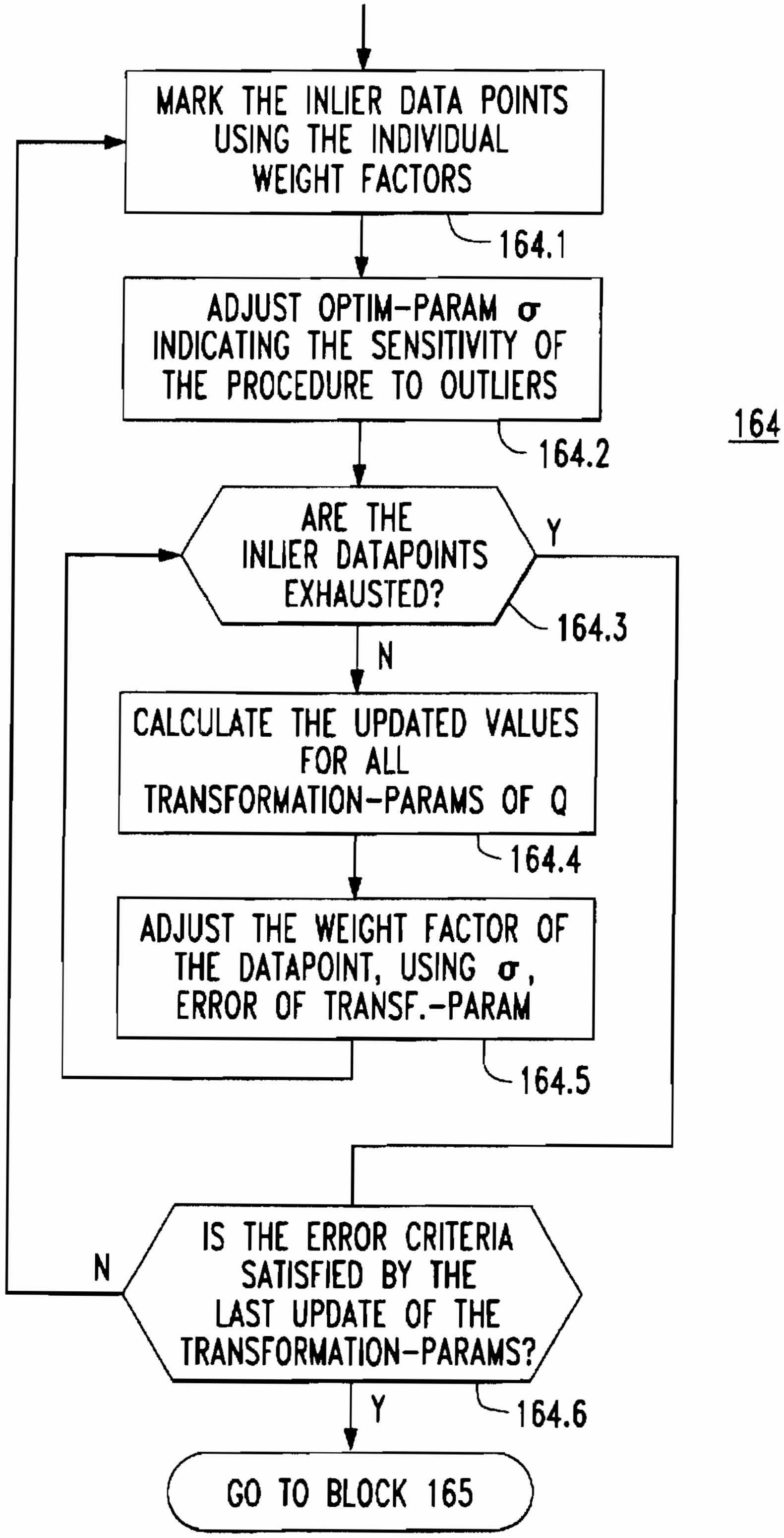

MARK THE INLIER DATA POINTS USING THE INDIVIDUAL WEIGHT FACTORS
164.1
ADJUST OPTIM-PARAM σ INDICATING THE SENSITIVITY OF THE PROCEDURE TO OUTLIERS
164.2
164
ARE THE INLIER DATAPOINTS EXHAUSTED?
Y
164.3
N
CALCULATE THE UPDATED VALUES FOR ALL TRANSFORMATION-PARAMS OF Q
164.4
ADJUST THE WEIGHT FACTOR OF THE DATAPOINT, USING σ, ERROR OF TRANSF.-PARAM
164.5
IS THE ERROR CRITERIA SATISFIED BY THE LAST UPDATE OF THE TRANSFORMATION-PARAMS?
N
Y
164.6
GO TO BLOCK 165

FIG. 10

APPARATUS FOR MATCHING X-RAY IMAGES WITH REFERENCE IMAGES

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to matching similar x-ray images and has particular application to computer controlled radiotherapy apparatus for automatically matching on-line the portal images generated during radiotherapy treatment on a treatment machine with simulation images generated prior to treatment on a simulation machine for determining that the desired target is actually being irradiated for the purposes of assessment, and/or controlling the treatment equipment.

2. Background Information

There are medical applications which require matching of x-ray images. For instance, in computer controlled radiotherapy, treatment beams of high energy radiation are directed at a tumor from a number of directions so as to maximize irradiation of the tumor while minimizing exposure of healthy tissue surrounding the tumor. Such radiotherapy treatment typically has two distinct phases: the simulation phase, and the actual treatment phase. In the simulation phase, the patient is placed on equipment similar to the treatment equipment except that it does not generate the high energy radiation beam. The simulation equipment is successively positioned to simulate the delivery of the sequence of treatment beams prescribed by the treating oncologist. This assures that the equipment can be positioned to deliver the required treatment beams and progressively move from one treatment beam to the next without collision between the equipment and the patient or between movable components of the equipment. During this procedure a low dosage x-ray image called the simulation image is taken. This simulation image, which generally has good contrast and detail because of the low energy of the x-ray beam used (in the kiloelectronvolt range) helps the oncologist to locate the position of the tumor and thereby establish the positions of the equipment components for delivering the successive treatment beams.

During the actual treatment phase, the patient is placed in the exact same position on the equipment as in the simulation before the regular-dosage x-ray radiation, typically in the megaelectronvolt range, is used to treat the patient. During this phase, another x-ray image is taken, which is called the portal image.

After completion of the treatment, the simulation and portal images are compared by an expert to determine whether the tumor, as identified in the simulation image, has been adequately treated with radiation in the portal image. If the coverage is not complete, the patient is scheduled for a corrective treatment.

The current accepted procedure involves the manual comparison of the portal and simulation images. Accurate manual comparison is quite challenging given the fact that the two x-rays are usually taken by different equipment and at different levels of radiation exposure. The latter fact implies that the tumor area is usually not visible in the portal x-ray, and thus the matching of the portal image with that of the simulation has to rely on manual estimation of dimensions from anatomical landmarks, which will not be clearly visible.

Conventionally, the portal images have been generated by using x-ray film which has to be developed. This is not a serious drawback where only a single or a few treatment beams are utilized. However, this x-ray film is a serious

limitation in computer controlled radiotherapy where a large number of treatment beams are used. Electronic portal imagers have been developed which generate a digitized image which can be displayed on an electronic display device. Unfortunately, the same problems exist as to the contrast and definition in the portal image generated electronically.

The problem of matching portal images with simulation images is compounded by the fact that the images have differences in orientation caused by skewing, scaling differences, rotation, translation and differences in perspective and curvature.

In stereotactic radiology, digitized computed tomography x-ray images and magnetic resonance images (MRI) have been automatically matched by applying scaling derived from known fixed dimensions of a steel frame which appears in both images. Such fixed landmarks of known dimensions are not available in conventional radiotherapy images.

There is a need, therefore, for apparatus for automatically matching x-ray images and particularly for matching portal images with simulation images in radiotherapy.

There is also a need for such apparatus which can match the portal and simulation images on-line for multiple treatment beams.

There is further need for such apparatus which can match portal images and simulation images having widely different contrast and definition and differences caused by skewing, rotation, scaling, perspective or curvature.

There is an additional need for apparatus for obtaining and maintaining alignment of a patient during computed controlled radiotherapy or for terminating the radiation beam if alignment becomes unacceptable.

SUMMARY OF THE INVENTION

These needs and others are satisfied by the invention which is directed to apparatus for automatically matching an x-ray image with a reference image, and particularly for matching the portal image with a simulation image for determining whether radiotherapy treatment has been adequate or for matching successive portal images for controlling operation of the radiotherapy equipment. In matching images, digitizing means digitizes the x-ray image such as the portal image to generate a first set of digital image signals or digital portal image signals (DPIS) in the case of the portal image. The digitizing means also digitizes the reference image such as the simulation image to generate second digital image signals or digital simulation signals (DSIS). Processing means process these digital image signals to generate matched digital image signals. The processing is performed without any prior knowledge of the physical dimensions of any of the features in the images. Output means generate for instance a display from the matched digital image signals and/or control the treatment/diagnosis equipment.

The processing means includes coarse alignment means which first effect a coarse alignment between the digital portal image signals and the digital simulation image signals. Coarse alignment is initiated by selecting seed points in the portal image represented by the DPIS and in the simulation image represented by the DSIS. Selection of the seed points can be done either interactively using a pointing device such as a mouse to select what appear to be corresponding points on displays of the two images, or automatically through use of x-ray opaque fiducials placed on the patient. In either case, the seed points are used to compute a transform between the two images. Means are then used to

apply the transform to one of the sets of digital image signals to transform points in that image to the coordinates of the other image thereby producing coarse aligned DPIS and DSIS.

Following coarse alignment, a fine alignment is performed. In implementing the fine alignment, the coarse aligned DPIS and DSIS are first prepared by selecting selected DPIS and selected DSIS for regions of the images which intersect or overlap, and preferably for a region of regular shape such as a rectangle within the intersecting regions of the images. The digital image signals for these regions are then enhanced to produce prepared images with similar dynamic range and pixel intensities. The fine alignment means includes means generating an updated transform from the prepared DPIS and DSIS, and means applying the updated transform to either the coarse or prepared DPIS and DSIS to generate the matched DPIS and DSIS.

The means generating the updated transform comprises means generating motion flow components from the prepared DPIS and DSIS and calculating means calculating the updated transform from the motion flow components. Preferably the means generating the motion flow components generates motion flow gradient components and the calculating means comprises means applying a robust optimization to calculate the updated transform. The means generating updated transform uses successive ascending levels of resolution of the prepared DPIS and DSIS to generate the updated transform.

In the tracking mode, the updated transform is used to track movement between successive sets of digital portal image signals. Tracking can be used to terminate the radiation if patient movement exceeds specified limits, or could be used to operate the patient positioning assembly to maintain the radiation beam in proper alignment with the area to be treated.

The invention can also be used to match x-ray images with other reference images which could be another x-ray image or another type of image.

BRIEF DESCRIPTION OF THE DRAWINGS

A full understanding of the invention can be gained from the following description of the preferred embodiments when read in conjunction with the accompanying drawings in which:

FIG. 1 is a schematic diagram of apparatus for implementing the invention.

FIG. 2*a* is a simplified illustration of a simulation image to which the invention can applied.

FIG. 2*b* is a simplified illustration of a portal image to which the invention may be applied.

FIG. 2*c* is a simplified illustration of a display superimposing the simulation and portal images of FIGS. 2*a* and 2*b* utilizing the invention.

FIGS. 3–11 are flow charts of software utilized to implement the invention in the apparatus of FIG. 1.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The invention is directed to matching x-ray images with reference images and will be described as applied to matching portal images generated in computer controlled radiotherapy with simulation images. However, it will be understood that the invention has wide application in matching other x-ray images such as those used in diagnosis, for example. As will be seen, the invention also has application

for tracking motion in successive portal images such as for controlling positioning of a patient or gating of the radiation beam.

Referring to FIG. 1, a simulation setup 1 is used for determining the location of the region such as a tumor within a patient 3 to be treated and for setting up the sequence of treatment beams. The setup equipment includes a gantry 5 mounted for rotation about a horizontal pivot 7 supported by a machine base 9. A low energy, in the kiloelectronvolt range, x-ray beam 11 is directed by a collimator 13 mounted on the gantry 5 along a path which extends transversely through an extension of the pivot 7.

The patient 3 is supported on a patient positioning assembly 15 which includes a couch 17 mounted on a support 19 for three dimensional translation relative to the support. The support 19, in turn, is mounted on a turntable 21. Through translation of the couch 17, rotation of the turntable 21 and rotation of the gantry 5 about the pivot 7, a plurality of treatment beams can be simulated. By sequencing the simulation equipment 1 through the positions required to generate the successive beams, it can be determined whether all of the required beams can be achieved and whether sequencing the movement of the equipment between beams must be adjusted to avoid collisions between the equipment and the patient or between components of the equipment.

The low energy x-ray beam 11 is used to generate simulation images by placement of an x-ray film 23 in line with the x-ray beam 11 on the other side of the patient 3 from the collimator 13. This simulation image is used to position the area of the patient to be treated, such as a tumor, at the isocenter of the setup, which is the intersection of the beam 11 with a projection of the pivot axis 7.

Following completion of the simulation, the patient 3 is transferred to the treatment setup 1'. As shown, the treatment setup at 1' is similar to the simulation setup 1, except that the x-ray beam 11' is in the megaelectronvolt range. A portal image is generated by the treatment setup 1'. This portal image can be captured by an x-ray film as in the simulation setup; however, it is preferred that an electronic portal imager 25 be used. If available, an electronic imager could also be used in place of the x-ray film 23 in the simulation setup 1.

As discussed above, the simulation image and the portal image can be quite different. One of the main reasons for this is the difference in the energy of the beams 11 and 11'. The invention can be used to match the simulation and portal images to determine if the treatment dosage was delivered to the proper treatment area. It can also be used to detect patient movement during treatment to terminate generation of the x-ray beam 11' if a movement exceeds proper limits, or to maneuver the equipment to maintain proper alignment.

The image matching system 27 includes a digitizer 29 which digitizes the simulation image such as produced on the x-ray film 23 and the portal image such as that generated by the electronic portal imager 25. In a more general sense, the matching system 27 matches an x-ray image, such as the portal image, with a reference image such as the simulation image.

The image matching system 27 further includes a processor 31 which includes a module for coarse alignment 33 followed by a module for fine alignment 35. The output of the processor can be matched portal (x-ray) and simulation (reference) images which are displayed on a display device 37. Associated with the display device 37 are interface devices 39 which can include a keyboard 41 and a pointing device 43, such as a mouse or a trackball.

FIGS. 2a–2c illustrate that the invention can be used to match a portal x-ray image with a simulation reference image. FIG. 2a represents a simulation image 45 generated using the simulation setup 1. The low energy x-rays used for this image produce an image with good contrast and detail, so that the outline 47 of the patient and bony structure 49 are shown as well as the tumor 51. FIG. 2b illustrates the portal image which being taken with the higher energy treatment beam shows the treated area 55 as a uniform dark spot. The irregular edge of the treated area 55 is produced by the leaves used in the collimator 13 to conform the beam 11' generally to the shape of the tumor. The remainder of the portal image 55 shows little detail and does not indicate the location of the bones. As can be seen, the two images 45 and 53 can be translated relative to each other, scaled differently, skewed and rotated (by 90° in the example). The two images can also be different in perspective and in curvature.

The coarse alignment module 33 produces a general alignment of the two images, and then the fine alignment module 35 uses robust motion flow to rapidly and accurately complete matching of the images. The display device 37 can present the matched images in different ways. In one embodiment, the display 37 alternates between the two images at about 6 to 20 Hz, but usually about 12 Hz, so that the observer views the images superimposed as a composite image 59, as shown in FIG. 2c. As can be seen in the example, the treated area 55' in the matched portal image, overlays the tumor 51' in the matched simulation image. In another type of display (not shown), the outline of the treated area from the portal image is projected onto the processed simulation image, so that it can be seen if the targeted tumor was in fact treated.

In performing the coarse alignment, a coarse transformation is applied to the digitized x-ray or portal image signals (DPIS) to convert them to the coordinate system of the digital reference or simulation image signals (DSIS). As will be seen, the information needed to generate this transformation can be generated interactively through selection of what appear to be corresponding points in the two images by the operator interactively using a pointer device 43 or automatically using x-ray opaque fiducials 61 which are placed on the patient in both the simulation setup and the treatment setup (see FIG. 1). The points so generated in either case are referred to as seed points. The coarse transform H from the portal image coordinates to the simulation coordinates is:

$$\begin{bmatrix} \text{simulation}_x \\ \text{simulation}_y \\ 1 \end{bmatrix} = \begin{bmatrix} \text{RotSkewScale}_a & \text{RotSkewScale}_b & \text{translation}_x \\ \text{RotSkewScale}_c & \text{RotSkewScale}_d & \text{translation}_y \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \text{portal}_x \\ \text{portal}_y \\ 1 \end{bmatrix} \tag{EQ. 1}$$

The (x y) vector denotes the column and row coordinates of the center of each of the seed points in the corresponding portal and simulation images. The four RotSkewScale components of the matrix describe the full affine transformation that is needed to coarsely align the images. In this stage, the placement of the fiducial or the interactive selection of the seed points need not be accurate as the next stage is able to accommodate for reasonably small deviations.

Using the results of the coarse alignment, the portal image is warped toward the simulation image. Then, overlapping regions of the two images are computer enhanced so that the

corresponding intensity levels are similar. Finally, the motion-flow, or the fine-scale transform is computed so that the portal image glides on the gradient of dissimilarity toward the simulation image. In this stage, a more comprehensive transformation model is used in which the input position vector is represented by:

$$\underline{X}(x) = \begin{bmatrix} 1 & x & y & 0 & 0 & 0 & x^2 & x \cdot y & 0 \\ 0 & 0 & 0 & 1 & x & y & x \cdot y & y^2 & x^2 \end{bmatrix} \tag{EQ. 2}$$

and the transformation matrix is represented by:

$$Q=[\alpha_0\alpha_1\alpha_2\alpha_3\alpha_4\alpha_5 P_0 P_1 c]^T \tag{EQ. 3}$$

so that the result is:

$$u(x;Q)=X(x)\cdot Q \tag{EQ. 4}$$

where Δ portal (x;Q)=u(x;Q) and portal (x)=X(x). The parameters α_0 through α_5 include the affine transform as in the coarse alignment, whereas the parameters P_0, P_1 include the perspective transformation, and c covers the deformation that can be caused by breathing, etc.

To recover the parameters of the vector Q we formulate the image dissimilarity as a result of motion-flow, or distance between the two images.

$$I(x,t)=I(x-(X(x)\cdot Q_{f,t+1})) \tag{EQ. 5}$$

for $\forall x \in f$, where f is the region of the image we compute the transformation over. In (EQ. 5), I(x) is the intensity function at point x, the image at t+1 is the portal image, and at t is the simulation image. By using various derivation techniques, we formulate the motion-flow using the gradient (or dissimilarity gradient) as below:

$$\nabla I(\underline{X}(x)\cdot Q_f) + \frac{\partial I}{\partial t} = 0 \tag{EQ. 6}$$

for $\forall x \in f$.

In this stage, a robust regression method is employed, using unconstrained optimization, to calculate the elements of Q (see (EQ. 3)). This technique enables us to cope with the 'reasonably small' deviations from the coarse alignment stage, as well as any residual dissimilarity between the two images. Using the robust technique ensures that only the dominant transformation will be recovered without running into the risk of being affected by the noise and residual errors.

FIGS. 3–11 are flow charts of software which implements the invention. FIG. 3 illustrates the main routine 100 which includes performing a coarse alignment, either interactively at block 110 or automatically at block 120. In both cases a rough approximation of the transformation between the portal image and the simulation image is calculated using Equation 1. The user then has the option of determining whether the rough approximation has provided a satisfactory alignment of the images at 130. If so, the procedure is completed. If not, a fine alignment is performed. As discussed, the invention can also be used to track patient movement, in which case the transformation between the two images is utilized at 140 to roughly determine the updated position of the fiducials. If requested by the user in image matching and during tracking, the images are prepared for the fine alignment at 150. The refined image transformation is then calculated at 160 and if the image

matching mode is selected as determined at 170, the transform is accomplished and the images are displayed at 180 in the manner discussed above. If the tracking mode has been selected at 190, the routine returns to 140 for generating the next position. The user again has the final decision at 200 to determine whether the image matching is satisfactory. If not, the routine returns to 110 and the rough calculation is re-initiated.

The procedure for calculating the rough approximation of the transformation interactively called for at block 110 in FIG. 3 is illustrated in detail in FIG. 4. The user selects corresponding seed points or areas in the portal image and the simulation image using, for instance, the mouse 43 as indicated at 111. The selected areas or points are then used to compute the rough transformation between the portal image and the simulation image by calling a procedure A as indicated at 112. This rough transform is then used to transform the portal image to simulation image coordinates by calling procedure B as indicated at 113. The images are then displayed on the monitor 37 as indicated at 114.

The details of procedure A used to calculate the rough transform are shown in FIG. 5. If the user has indicated an area as determined at A1, the system automatically selects random points from inside the area as corresponding as indicated at A2. Then, or if the user has selected points rather than an area, the corresponding point pairs are used to calculate the transform parameters using the least squares (LSQ) method as indicated at A3.

The details of procedure B for transforming the portal to simulation coordinates is shown in FIG. 5. First, the row and column limits of the resulting transformed portal image are determined at B1 using the transformation matrix H, which is the inverse of Equation 1. The resulting portal image is then raster scanned at B2, and for each pixel the location is determined using the transformation. The intensity value for each pixel is calculated next using linear interpolation between the surrounding pixel locations in the original portal image.

The routine 124 for performing the coarse alignment automatically using fiducials on the patient is shown in FIG. 7. The x-ray opaque fiducials 61 are detected in both the portal and simulation images at 121 and the corresponding markers are identified at 122. The image transform is then computed at 123 using procedure A of FIG. 5 and the centroid of each of the markers as the seed points. The portal image is then transformed to simulation coordinates using the computed transformation and procedure B of FIG. 6. When in the matching mode as determined at 125, the images are displayed at 126 in the manner discussed above in connection with FIGS. 2*a–c*.

The routine 150 for preparing the coarse aligned digital image signals for fine alignment is shown in FIG. 8. First, the region of intersection over overlap between the simulation and portal images is calculated at 151 using the transformation of Equation 1. Next, the largest rectangular region that fits within the intersection region is calculated at 152. Other regular geometric shapes, such as a square and so forth, could be used in place of the rectangle. New images representing the rectangular intersection region of the portal and simulation image are formed at 153. These resulting images are then enhanced at 154 to generate prepared digital image signals. Various forms of enhancement such as histogram equalization, lapalcian of the Gaussian, high-pass filtering and other techniques are used to produce the prepared images with similar dynamic range and pixel intensities.

FIG. 9 illustrates the routine 160 for calculating the updated transformation for a fine alignment. This process is performed at several levels of resolution of the digital image signals beginning with the lowest resolution, which in the example is about one-eighth resolution. Thus, at 161 the images at the lowest resolution for the prepared portal and simulation images are formed. These images are updated using the latest updated transformation parameters, that is, transformation parameters calculated at the previous level of resolution, at 162. An important part of the invention is that robust motion flow is used to perform the fine alignment. In particular, the motion flow gradient components are generated at 163. Application of motion flow using gradient components is described by M. J. Black and P. Anandan in a paper entitled, "*A Framework For The Robust Estimation Of Optical Flow*" published in Proc. 4th Intl. Conf. on Computer Vision (ICCV 93), Berlin, Germany, May 1993. Motion flow is applied to the motion required to cause pixels on one image to flow into alignment with corresponding pixels in the other image. Robust motion applies to the motion by which most of the pixels which have moved have moved similarly, while there may be others exhibiting different motion. The updated image transformation parameters are then calculated at 164 using robust optimization. If the upper limit of resolution has not been reached as determined at 165, then the resolution is incremented at 166 and updated transformation parameters are recalculated at the new level of resolution.

When the highest level of resolution has been reached at 165, the final transformation matrix Q is generated at 167. The details of the routine for calculating the updated image transformation parameters using robust optimization of block 164 in FIG. 9 is shown in FIG. 10. As described in the paper by Black and Anandan discussed above, the robust motion is represented by data points called inliers. Those exhibiting other motion are identified as outliers. In the present invention, the data points are the pixel values. The pixels are successively separated into inliers and outliers based upon their contribution to a consistent motion flow vector. The pixels in the inlier set are used to calculate the dominant motion flow, and their contribution to it is dependent on their weight factors which are calculated during the robust optimization.

Referring particularly to FIG. 10, a loop is entered at 164.1 where each of the inlier points is marked using individual weight factors. Initially, the weight factors of the pixels are all set to 1 so that all of the pixels are inliers. At 164.2, an optimization parameter, σ, which determines the sensitivity of the procedure to outliers is set. The weight factors are dependent on this parameter, σ. The lower the value of σ, the more points are eliminated as inliers and the closer the inliers become to the current estimate of the motion flow vector. Hence, a large σ is used initially so that all points are included. On successive loops, σ is lowered to eliminate more and more outliers. This lowering of σ is referred to as σ scheduling. The σ scheduling must be done carefully. If σ is lowered too fast, a solution may be missed, while on the other hand, lowering σ too slowly increases the processing time. In accordance with the invention, σ is lowered depending upon the largest error in the motion flow parameters. Following this, another loop is entered at 164.3 in which each of the inlier data points is used in the calculation of the updated values for the transformation parameters of the Q matrix at 164.4. The equations used at 164.4 are derived preferably using the conjugate gradient, although gradient descent can also be used. In addition, motion flow and robust statistics are used in deriving equations for determining the transformation parameters. The error in the transformation parameters, which is the change

from the last calculation, as well as σ, are used at **164.5** to adjust the weight factors for the pixels. When all of the inlier data points/pixels have been used as determined at **164.3**, a check is made at **164.6** to determine if the solution has converged to the desired degree. If not, the routine returns to **164.1** and the inlier data points are again marked using the updated weight factors.

FIG. **11** illustrates the tracking routine on **140**. As indicated at **141**, the incremental updates and the transform H and/or Q are combined so that the transform always relates back to the original simulation or reference image. On the initial pass through the tracking routine, the then current portal image replaces the simulation image if used, and then a new portal image is acquired at **143**. As tracking continues, successive portal images are matched with the next preceding portal image to generate the updated transform. As indicated at **144**, the successive positions of the fiducials or changes in the pattern of the fiducials from successive portal images is used to generate tracking signals for controlling the radiotherapy equipment such as turning the beam on and off and/or driving the patient positioning assembly.

While specific embodiments of the invention have been described in detail, it will be appreciated by those skilled in the art that various modifications and alternatives to those details could be developed in light of the overall teachings of the disclosure. Accordingly, the particular arrangements disclosed are meant to be illustrative only and not limiting as to the scope of invention which is to be given the full breadth of the claims appended and any and all equivalents thereof.

What is claimed is:

1. Apparatus for automatically matching a portal image with a simulation image, said apparatus comprising:

means digitizing said portal image and simulation image to generate digital portal image signals (DPIS) and digital simulation image signals (DSIS), respectively;

processing means processing said DPIS and said DSIS to generate matched DPIS and DSIS; and

output means for generating an output from said matched DPIS and DSIS.

2. The apparatus of claim **1**, wherein said processing means comprises coarse alignment means generating coarse aligned DPIS and DSIS from said DPIS and DSIS, and fine alignment means generating said matched DPIS and DSIS from said coarse aligned DPIS and DSIS for overlapping regions of said simulation and portal images.

3. The apparatus of claim **2**, wherein said coarse alignment means comprises means selecting corresponding seed points in said portal image represented by said DPIS and said simulation image represented by said DSIS, means computing a transform between said portal image and said simulation image from said corresponding seed points, and means applying said transform to one of said DPIS said DSIS to generate with the other of said DPIS and DSIS said coarse aligned DPIS and DSIS.

4. The apparatus of claim **3**, wherein said means selecting corresponding seed points comprises interactive means selecting corresponding points in displays generated from said DPIS and DSIS.

5. The apparatus of claim **3**, wherein said means selecting corresponding seed points comprises means detecting x-ray opaque fiducials in said DPIS and said DSIS, and means identifying corresponding fiducials in said DPIS and DSIS as said corresponding seed points.

6. The apparatus of claim **3**, wherein said fine alignment means comprises means generating prepared DPIS and DSIS from said coarse aligned DPIS and DSIS, means

generating an updated transform from said prepared DPIS and DSIS, and means applying said updated transform to one of said coarse and prepared DPIS and DSIS to generate said matched DPIS and DSIS.

7. The apparatus of claim **2**, wherein said fine alignment means comprises means generating prepared DPIS and DSIS from said coarse aligned DPIS and DSIS, means generating an updated transform from said prepared DPIS and DSIS, and means applying said updated transform to one of said coarse and prepared DPIS and DSIS to generate said matched DPIS and DSIS.

8. The apparatus of claim **7**, wherein said means generating said prepared DPIS and DSIS comprises means selecting selected DPIS and selected DSIS for regions of images represented by said DPIS and DSIS which intersect.

9. The apparatus of claim **8**, wherein said means generating said prepared DPIS and DSIS further includes means enhancing said selected DPIS and DSIS.

10. The apparatus of claim **9**, wherein said means selecting said selected DPIS and selected DSIS further includes means selecting DPIS and DSIS within a portion of regions of images represented by said DPIS and DSIS, which have a predetermined regular shape.

11. The apparatus of claim **7**, wherein said means generating said updated transform comprises means generating motion flow components from said prepared DPIS and DSIS and calculating means calculating said updated transform from said motion flow components.

12. The apparatus of claim **11**, wherein said means generating motion flow components generates motion flow gradient components, and said calculating means comprises means applying a robust optimization to calculate said updated transform.

13. The apparatus of claim **12**, wherein said means generating said updated transform comprises utilizing said means generating motion flow gradient components and said calculating means repetitively using successive ascending levels of resolution of said prepared DPIS and DSIS.

14. The apparatus of claim **7**, wherein said means generating said updated transform comprises means using successive ascending levels of resolution of said prepared DPIS and DSIS to generate said updated transform.

15. The apparatus of claim **7**, wherein said means generating said updated transform comprises means applying robust motion flow to said prepared DPIS and DSIS.

16. The apparatus of claim **15**, wherein said means applying robust motion flow to said prepared DPIS and DSIS applies robust motion flow to successive ascending levels of resolution of said DPIS and DSIS.

17. The apparatus of claim **1**, wherein said output means comprises display means generating a display from said matched DPIS and DSIS.

18. The apparatus of claim **1**, wherein said output means comprises tracking means tracking movement in said image represented by said DPIS.

19. The apparatus of claim **18**, wherein said output means further includes positioning means positioning a patient relative to a radiation beam which generates said portal image, and means controlling said positioning means in response to movement tracked by said tracking means.

20. The apparatus of claim **18** wherein said output means includes means controlling generation of a radiation beam producing said portal image in response to movement tracked by said tracking means.

21. Apparatus for matching portal images to control radiotherapy/diagnosis equipment, said apparatus comprising:

means digitizing successive portal images to generate successive sets of digital portal image signals (DPIS); and

tracking means tracking movement between successive sets of DPIS.

22. The apparatus of claim 21, wherein said tracking means comprises means generating an updated transform between successive portal images by applying robust motion flow to said successive sets of DPIS and means using said updated transform to track said movement between said successive sets of DPIS.

23. The apparatus of claim 22, wherein said means generating said updated transform comprises means generating motion flow components from said successive sets of DPIS, and means calculating said updated transform between successive portal images using said motion flow components.

24. The apparatus of claim 23, wherein said means generating motion flow components generates motion flow gradient components, and wherein said calculating means comprises means applying a robust optimization to calculate said updated transform.

25. The apparatus of claim 24, wherein said means generating said updated transform comprises means utilizing said means generating motion flow gradient components and said calculating means repetitively using successive ascending levels of resolution of said successive sets of DPIS.

26. Apparatus for automatically matching an x-ray image with a reference image, said apparatus comprising:

means digitizing said x-ray image and reference image to generate first digital image signals and second digital image signals, respectively;

processing means processing said first and second digital signals without input of any physical dimensions of any features within said images to generate matched digital image signals; and

display means generating a display from said matched digital image signals.

27. The apparatus of claim 26 wherein said processing means comprises coarse alignment means generating coarse aligned digital images signals from said first and second digital image signals, and fine alignment means generating a transform between said coarse aligned digital image signals for overlapping regions of said x-ray and reference images utilizing robust motion flow, and means applying said transform to one of said coarse aligned digital image signals to generate said matched digital image signals.

28. The apparatus of claim 27 wherein said fine alignment means comprises means enhancing said coarse aligned digital image signals to generate prepared coarse aligned image signals having similar dynamic ranges and intensities, and means generating said transform between said prepared coarse aligned digital image signals utilizing robust motion flow.

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UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRRECTION

Page 1 of 2

PATENT NO. : 5,784,431
DATED : July 21, 1998
INVENTOR(S) : Kalend, et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

At [56] References Cited, please add the following patents and publications.

OTHER DOCUMENTS

		Digital portal image registration by sequential anatomical matchpoint and image correlations for real-time continuous field alignment verification, Brian J. McParland and J. Carl Kumaradas, Phys. 22(7), July 1995, pp. 1063-1075.
		Neutral Network Object Recognition for Inspection of Patient Setup in Radiation Therapy Using Portal Images, Susan S. Young, et al., 1996 IEEE, pp. 3418-3421.

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

Page 2 of 2

PATENT NO. : 5,784,431

DATED : July 21, 1998

INVENTOR(S) : Kalend, et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 9, line 37, after "means" insert --comprising coarse alignment means--.

Column 9, line 38, after "generate" insert --coarse aligned DPIS and DSIS, means determining from said coarse aligned DPIS and DSIS overlapping regions of said simulation and portal images, and fine alignment means generating--.

Column 9, line38, after "DSIS" insert --from said coarse aligned DPIS and DSIS for said overlapping regions of said simulation and portal images--.

Cancel Claim 2.

Column 9, line 47, change "2" to --1--.

Column 10, line 5, change "2" to --1--.

Signed and Sealed this

Twenty-third Day of February, 1999

Attest:

Q. TODD DICKINSON

Attesting Officer

Acting Commissioner of Patents and Trademarks